

**Advanced Composite Materials for New England's Transportation  
Infrastructure: A Study for Implementation and Synthesis of  
Technology and Practice**

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16. Abstract <p>Advanced composite materials (ACMs) have been used to a limited extent in the transportation infrastructure. Their widespread application has been hindered in the past because of lack of design documents and paucity of documented performance under the diverse environmental conditions encountered in the transportation infrastructure. The current research project focused on identifying obstacles and developing a methodology to increase the use of ACMs within the transportation infrastructure in New England. The following activities were undertaken to achieve the goal of the project: (1) creation of development and compilation of questionnaires sent to engineers in transportation agencies, fabricators, and researchers; (2) creation of a web site for information dissemination; (3) conducting meetings at transportation agencies; (4) identification of perceived obstacles for using ACMs in transportation infrastructure projects; and (5) development of a methodology to expand the use of ACMs in future transportation infrastructure projects in New England.</p>					
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# SI\* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
<b>AREA</b>				
in <sup>2</sup>	square inches	645.2	millimetres squared	mm <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	metres squared	m <sup>2</sup>
yd <sup>2</sup>	square yards	0.836	metres squared	m <sup>2</sup>
ac	acres	0.405	hectares	ha
mi <sup>2</sup>	square miles	2.59	kilometres squared	km <sup>2</sup>
<b>VOLUME</b>				
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	Litres	L
ft <sup>3</sup>	cubic feet	0.028	metres cubed	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	metres cubed	m <sup>3</sup>
<b>MASS</b>				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
<b>TEMPERATURE (exact)</b>				
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

NOTE: Volumes greater than 1000 L shall be shown in m<sup>3</sup>

## APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
<b>AREA</b>				
mm <sup>2</sup>	millimetres squared	0.0016	square inches	in <sup>2</sup>
m <sup>2</sup>	metres squared	10.764	square feet	ft <sup>2</sup>
ha	hectares	2.47	acres	ac
km <sup>2</sup>	kilometres squared	0.386	square miles	mi <sup>2</sup>
<b>VOLUME</b>				
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m <sup>3</sup>	metres cubed	35.315	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	metres cubed	1.308	cubic yards	yd <sup>3</sup>
<b>MASS</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
<b>TEMPERATURE (exact)</b>				
°C	Celsius temperature	1.8C+32	Fahrenheit temperature	°F

°F	32	98.6	212
°C	0	100	212
°F	-40	0	100
°C	-40	0	100

\* SI is the symbol for the International System of Measurement

## Summary

The use of advanced composite materials (ACMs) in transportation infrastructure initiated as a result of deterioration occurring in the transportation network over the years. At the time these materials had been used primarily in the aerospace, automotive, and sports industries. Their physical and mechanical properties made them amenable for use in bridge structures, particularly to retrofit existing damaged or deteriorated structural elements or as replacement of decks deteriorated by corrosion. It was clear, however, that the materials had a much larger potential than just for these limited number of applications in the civil engineering market.

In light of this, the New England Transportation Consortium (NETC) funded the current research project, intended to provide a summary of current practices and examine ways to expand the use of ACMs in New England's transportation infrastructure. The main goals of the project were to: (1) form a network of participants in the advanced composite materials market, including ACM product fabricators, engineers at transportation agencies in New England, and researchers with experience using ACMs; (2) identify obstacles for wider use of these materials in the transportation infrastructure as perceived from different participants in this network; and (3) establish a methodology that could be implemented within transportation agencies to expand use of ACMs in other applications than those used to date. Several activities were conducted as part of the project to achieve these goals.

Questionnaires were prepared and sent to members of the ACM network to identify perceived obstacles for the wider use of these materials. Responses were received from individuals in the six transportation agencies (DOTs, highway departments, or agencies) in New England, as well as from fourteen individuals representing different ACM fabricators. Also, four project meetings were held involving engineers, researchers, and fabricators of ACMs where additional information was collected. All the information gathered throughout the project was summarized into a project web site specifically created as a portal for information dissemination ([http://www.ecs.umass.edu/cee/NETC\\_01-1](http://www.ecs.umass.edu/cee/NETC_01-1)). Of the perceived obstacles from the different network participants the following were considered to be the most prevalent:

- High cost of ACMs compared with traditional civil engineering materials.
- Lack of design guidelines and standardized products that would allow engineers to verify design calculations.
- Limited information on the long-term performance of ACMs under combined environmental actions.
- Limited familiarity of design engineers with ACMs.
- Lack of transparency and extensive proprietary product information within the ACMs industry.

Existing applications of ACMs in transportation projects in the different New England states had a major role in identifying obstacles encountered during the design and implementation process, and also permitted to establish a potential methodology to expand the number of applications of these materials in future projects. The main recommendations for a successful implementation of ACMs in future projects include:

- Increase database of projects with supplemental funding from IBRC.
- Continue to monitor performance of existing applications.
- Familiarize engineers with materials through seminars/workshops.
- Establish close communication between engineers and producers.
- Identify potential applications where ACMs would be beneficial.
- Establish close collaborations among design engineers, fabricators, and researchers to develop novel applications of ACMs that are cost-competitive and more durable than traditional civil engineering materials.

It is believed that ACMs will continue to be used in transportation infrastructure projects because they offer a possible solution to the many problems caused by deterioration of the transportation infrastructure. Their expansion beyond the limited number of applications to date will depend on establishing effective collaborations and opening communication channels between engineers and fabricators to clearly identify the required performance goals of each particular application.

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## **List of Acronyms**

AASHTO	American Association of State Highway Transportation Officials
ACI	American Concrete Institute
ACM	Advanced Composite Material
CFRP	Carbon Fiber-reinforced Polymer
DOT	Department of Transportation
FHWA	Federal Highway Administration
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber-reinforced Polymer
IBRC	Innovative Bridge Research and Construction Program
NCHRP	National Cooperative Highway Research Program
NEBT	New England Bulb Tee
NETC	New England Transportation Consortium
RTM	Resin Transfer Molding

# **1. Introduction**

## **1.1 Objectives**

The use of advanced composite materials (ACMs) in infrastructure has received considerable attention over the last decade, both in the United States and in other parts of the world. Implementation of these materials in the transportation infrastructure, however, has not been as widespread as in other industries such as the automotive or aerospace fields. Although these materials have a significant track record in these other industries, their use in civil engineering applications spans only a few decades. Most of the applications in civil engineering have served as demonstration projects, where the materials have been shown as potential substitutes to traditional civil engineering materials (wood, steel, aluminum, concrete, etc.). ACMs have been shown to provide a plausible alternative to traditional materials in transportation infrastructure applications, mainly because of the severe infrastructure deterioration observed in recent years. These materials promise to increase the service life of bridges and their components, and do not suffer from degradation from use of de-icing chemicals or chloride attack in coastal regions. However, their long-term performance under combined environments common in transportation infrastructure has been questioned in recent years. The widespread, systematic use of ACMs in transportation infrastructure is not yet prevalent because of different reasons including lack of design standards applicable to transportation infrastructure projects, lack of information on long-term performance of these materials, and limited experience and knowledge of engineers on the performance of ACMs in field applications.

The main objective of this research project was to investigate procedures to increase the effective use of ACMs in the transportation infrastructure within New England. A series of tasks were performed throughout the project as described in Section 1.2 to achieve this objective. The ultimate goal was to establish a methodology that could be employed to facilitate implementation of ACMs in future transportation infrastructure projects. This methodology was developed building on the experience that individual states have developed over the years when using ACMs in a limited number of projects.

## **1.2 Scope of Research**

To achieve the goal of the research project, several tasks were undertaken to identify a methodology that could potentially expand the use of ACMs in future infrastructure projects. An extensive literature review was conducted to identify products and applications that have been used in other states and countries to determine if the technology could be adapted for the New England region. Areas of ongoing research on the use of ACMs were also identified through this literature search. The research information was collected by conducting a traditional library-based search, while field applications and product availability were determined from information obtained through internet-based searches or articles published in professional magazines.

Information on the use of ACMs in the six New England states was obtained from fabricators, researchers, and transportation agency engineers through questionnaires and personal communications. These groups contribute in different areas to the implementation of ACMs in transportation infrastructure applications and therefore constituted a network of participants for the project. The responses from the network participants were used to identify perceived obstacles on the wider use of composites in the transportation infrastructure from different perspectives of individuals involved with this industry. A forum for information exchange was formed by scheduling project meetings at four state DOTs during 2005 (Connecticut, Massachusetts, New Hampshire, and Vermont), a presentation made at the AASHTO T-6 Committee meeting in Rhode Island in the summer of 2005, and two videoconferences with the members of the project technical committee. Composite manufacturers attended the meeting in New Hampshire and provided useful information on their capabilities and perspective for enhancement of the use of ACMs in the transportation infrastructure.

Results of all project activities were summarized and added into a web site developed for the project ([www.ecs.umass.edu/cee/NETC\\_01-1/](http://www.ecs.umass.edu/cee/NETC_01-1/)). The project web site served as a portal for dissemination of information and as a single access point to all the information collected throughout the project. The project web site includes a list (with contact information) of manufacturers of composite materials in New England and highlights existing applications of advanced composite materials in transportation infrastructure projects in the six New England states.

Finally, a proposed methodology to increase the use of ACMs in the transportation infrastructure was developed from the knowledge gained through project meetings, questionnaires, and personal communications with the different participants of the network. This methodology, which is based on positive experiences gained in previous transportation projects using ACMs, is divided into several steps that engineers at transportation agencies can follow for implementation of ACMs in future projects.

### **1.3 Report Organization**

This report is divided into five chapters. The first chapter serves as an introduction and summarizes the project objectives and scope. Background material on fabrication processes and common constituent materials for ACMs is presented in Chapter 2. Typical applications related to the transportation infrastructure where ACMs have been used in the past are also presented in this chapter. Potential uses where these materials could be used effectively are indicated. Information gathered to investigate the current state of use of ACMs in the New England transportation infrastructure is discussed in Chapter 3. The chapter starts off by summarizing representative responses from two groups of the network of participants: fabricators and end users. Obstacles indicated from these two groups on the wider use of these materials in transportation infrastructure projects are presented and discussed. Possible alternatives to reduce or eliminate these obstacles are presented where appropriate.

Details of existing transportation infrastructure projects within New England where ACMs have been used in the past were collected and serve as a fundamental

component of this project. The important role that demonstration projects play in identifying a methodology to facilitate the implementation of these materials in future projects should not be overlooked. For this reason, Chapter 4 is devoted entirely to existing applications of ACMs in New England. Finally, project conclusions and recommended steps to further the use of ACMs in future transportation infrastructure projects are given in Chapter 5.

## 2. Background

This section presents a summary of advanced composite materials, their types, and manufacturing procedures most commonly used for products in the transportation infrastructure. Specific details of mechanical (short and long-term), thermal, chemical, or environmental properties of ACMs can be found in textbooks on fiber-reinforced polymer composites (e.g. Hollaway 1993; Hull and Clyne 1996; Hollaway and Head 2001).

### 2.1 Advanced Composite Materials

Advanced composite materials (ACMs) have been used for many years in the aerospace and automotive industries. Their use has expanded recently into Civil Engineering, most notably in rehabilitation of existing structures. ACMs are made up of two different materials: fibers and resins. Fibers are embedded in a polymer matrix (resin) that serves to form specific shapes for the desired application. Because of this, ACMs are also known as fiber-reinforced polymer (FRP) composites. The terms ACM or FRP are used interchangeably to refer to advanced composite materials in this report.

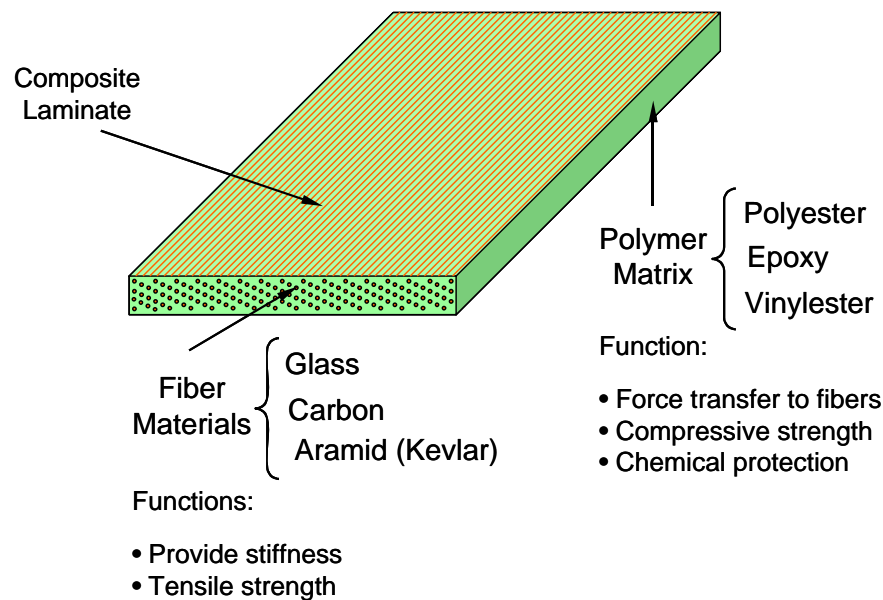
Fibers and resins contribute to specific physical and mechanical properties of the resulting composite materials affecting their performance in service. Because of the relatively large variety of fibers and resins in the market, a wide variety of material properties can be expected in ACMs that can make them specifically suitable for particular applications. The function that each material component has in the resulting composite material is discussed in this section. The most common types of fibers and resins used for transportation infrastructure applications are discussed in sections 2.1.2 and 2.1.3, respectively. Typical manufacturing techniques of composite materials are presented in Section 2.1.4.

#### *2.1.1 Role of Fibers and Resins in Composite Material Properties*

As in any composite material, mechanical properties of polymer composites are affected by the properties of the constituent materials (fibers and resins). Fibers primarily control the stiffness and strength of the resulting composite material. The arrangement of fibers (fiber architecture) within a composite material strongly affects many of its properties. Fiber volume fraction, defined as the ratio between fiber volume and composite volume, is typically used as a measure of fiber content in composites. Higher fiber volume fractions result in composites with higher tensile strength and modulus. Fibers can be arranged ideally in hexagonal, square, or irregular lattices (fiber packing). There is a theoretical upper limit on the number of fibers that can be accommodated for each fiber packing arrangement. For example, fibers placed in contact forming hexagonal or square arrays result in theoretical fiber volume fractions of 0.91 or 0.79, respectively. A practical upper limit on fiber volume fraction is approximately 0.7 (Hull and Clyne 1996).

Fiber orientation can also be used to tailor the mechanical properties of composites to meet a desired performance. Composite laminates, composite materials formed by successive layering of fibers embedded in a polymer resin matrix, mainly derive their mechanical properties from the resulting arrangement of individual laminae and the fiber architecture within them. An example of a unidirectional (all fibers oriented along the longitudinal axis of the composite) is illustrated in Figure 2.1.

The resin forms a matrix surrounding the fibers and is mainly responsible for stress transfer between fibers and protects fibers from chemical or environmental attack. The surface area between fibers and matrix is known as the interface between the materials. Stress transfer between matrix and fibers occurs at the interface, so fiber surfaces are often treated during fabrication with chemical agents that promote bonding and ensure compatibility between fiber and resin (fiber sizing).



**Figure 2.1 – Example of unidirectional composite laminate**

### **2.1.2 Fibers**

The most common types of fibers used currently in the transportation infrastructure are either inorganic (E-glass) or organic (carbon, aramid). Basalt fibers are currently being investigated as a new type of reinforcement for polymers in transportation infrastructure applications as part of another NETC project (NETC No.03-7). Fibers are produced in many different forms including continuous strands, rovings, chopped strands, woven rovings, mats, woven fabrics, and stitched fabrics.

Continuous strands are formed by twisting glass fiber filaments (approximately 200 fibers/strand) bonded together using a surface treatment (sizing agent) during fabrication of the fibers. Glass fiber filaments are fabricated using a drawing process resulting in glass fiber diameters from 3 to 24  $\mu\text{m}$  in diameter. Untwisted bundles of glass fibers are referred to as rovings. The diameter of individual carbon fiber filaments

ranges between 5 and 8  $\mu\text{m}$ . Carbon fiber filaments can be combined to form tows containing between 5,000 and 12,000 filaments per tow (Hollaway 1993).

Strands can be cut into short pieces to form chopped strands that can be used as randomly oriented reinforcement in ACMs. Chopped strand can also be bonded together to form chopped strand mats for reinforcement of the polymer material matrix. Woven rovings refer to continuous strands that are weaved to form sheets that can be used in the hand layup or pultrusion manufacturing processes (see Section 2.1.4). Fiber mats can be fabricated using chopped or continuous strands bonded together using a chemical binding agent. Continuous strand mats can achieve higher strengths than chopped strand mats because less stress transfer occurs through the matrix. Woven fabrics are manufactured by weaving strands in different patterns and fiber orientation. Fiber strands are bent slightly (crimped) to form the weave pattern, contributing to a lower strength of woven fabrics compared with unidirectional fiber laminates with the same fiber volume content. Stitched fabrics are formed using primarily unidirectional yarns connected together using a light filament that holds fibers in place and avoids fiber crimping. Composites made from stitched fabrics can achieve higher strength than those fabricated from woven fabrics by eliminating undesirable stresses caused by straightening of fibers as the composite is loaded in tension.

Fibers can be applied in ACMs in one direction (unidirectional) or multiple directions at varying angles. Fiber orientation is an important parameter that affects the mechanical properties of the finished ACM product. The resulting product can behave as a quasi-isotropic material (random fiber orientation), an orthotropic material (distinct properties in orthogonal directions that results from orthogonal placement of fibers in different material layers), or an anisotropic material (different properties in all directions) depending on fiber orientation. Fiber orientation can, therefore, be used to fabricate a composite with the desired properties in different directions.

### ***2.1.3 Polymer Matrices***

One of the characteristics of advanced composite materials is that they typically use a polymer resin as the matrix material for the composite. Polymer resins can be broadly classified into two main groups: thermoplastic and thermosetting resins. Thermoplastic resins (thermoplastics) are polymers that change from a rigid solid to a viscous liquid after heating. Thermosetting polymers (thermosets), on the other hand, do not change from solid to liquid after hardening (curing). In other words, the solidification that occurs after polymerization of the materials during the curing process is reversible in thermoplastics and irreversible in thermosets. The ACMs used in transportation infrastructure applications are typically fabricated using thermosetting polymer resins.

The most common thermosetting polymer resins used to fabricate ACMs for transportation infrastructure applications are polyesters, vinylesters, epoxies, or phenolics, although this last type of resins are not stable under ultraviolet radiation (Hollaway and Head 2001). A wide range of physical and mechanical properties can be obtained from these four types of resins. Thermosetting polymers are transformed from a liquid state to a solid state through molecule cross-linking eventually forming a three-

dimensional network. The mechanical properties of the cured polymer are strongly affected by the original molecular composition of the polymer and the density and length of these cross-links. The properties of the cross-link network are defined during fabrication of the polymer, and are affected strongly by the curing method used during the polymerization process (Hull and Clyne 1996). Although some polymers require high curing temperatures, polymers that cure at ambient temperatures are sometimes useful for some transportation infrastructure applications where the composites are formed in the field.

Specific properties of matrix materials that are of particular importance for the performance of the finished composite material include those affecting their interaction with the specific fiber reinforcement used in the composite and those controlling their chemical resistance to different agents. Polymer matrix selection has to be done in combination with the fibers being selected for a particular application. The matrix resistance to particular environmental conditions (e.g. acid or alkaline environments) can be enhanced through the use of fillers in the polymer resin matrix during fabrication of the composite. For appearance of the finished composite product, pigments can also be added to the polymer matrix (Hollaway 1993).

#### ***2.1.4 Manufacturing Processes of Advanced Composite Materials***

The type of manufacturing process used affects mechanical properties of the composite material. The fiber volume that can be placed in a composite is dependent on the manufacturing procedure, and as mentioned before fiber volume ratio contributes significantly to strength and stiffness of the material. Composite material manufacturing processes can be broadly classified into two main categories: manual and automated procedures. Manual procedures produce composite materials with higher variability compared with automated procedures. Also, the high pressures required to fully wet fibers in a tightly packed arrangement are only achievable using automated procedures. Automated fabrication procedures are, therefore, more desirable than manual procedures but some applications require the use of manual procedures. The following two sections describe the main manual and automated procedures used to fabricate composites in the transportation infrastructure.

##### **(a) Manual Procedures**

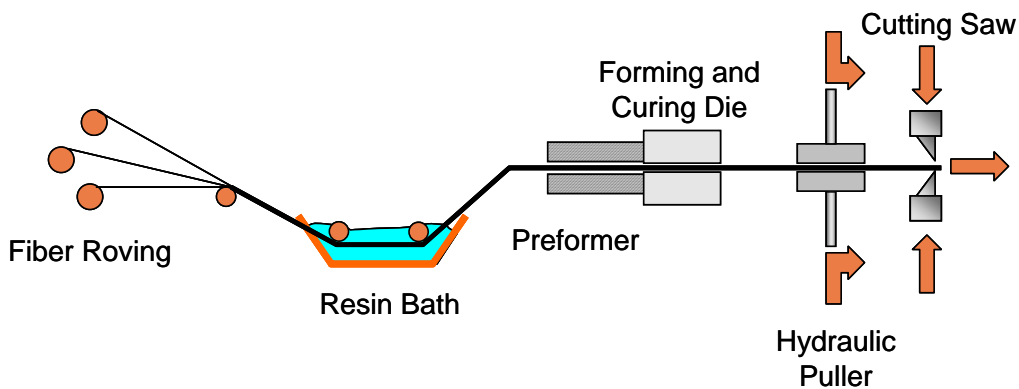
In all manual composite manufacturing processes, application of the component materials always involves hand application of the component materials to different degrees. For this reason, manual methods are often referred to as hand layup procedures, and consist of forming the composite laminates by hand layering fibers and resin. These methods are often used when the composite is applied to the surface of an existing structural component for strengthening purposes. A large variety of fiber sheets and fabrics are produced that can be used with this fabrication procedure. Most of these sheets have fibers placed unidirectionally with either a backing paper or transverse stitching to control fiber fraying during placement. Fibers can be dry or partially wetted (pre-pregs).

The resins used in manual procedures often consist of ambient-curing epoxies. Epoxy is applied to the fibers by hand using paint rollers. To ensure complete fiber wetting, epoxy is allowed to impregnate fibers for a given period of time (typically around 30 minutes) prior to applying subsequent layers of fibers or resin. One of the advantages of using manual methods is that the composite material adopts the form of the shape to which it is being applied, so it can conform easily to regular or irregular shapes. An advantage of this procedure is that material application does not require a high degree of skill or specialized training.

#### (b) Automated Procedures

In these methods, fiber and resin are applied automatically. Fibers can be either continuous or chopped. Partially automated procedures also exist where fabrication requires application of some of the materials by hand. The two main fully automated procedures used for transportation infrastructure applications are pultrusion and filament winding. Among the partially automatic procedures, compression molding and resin transfer molding are the most common methods. These fabrication methods are described in detail in most books covering advanced composite materials, so only a very brief description of the most important methods is presented in this report.

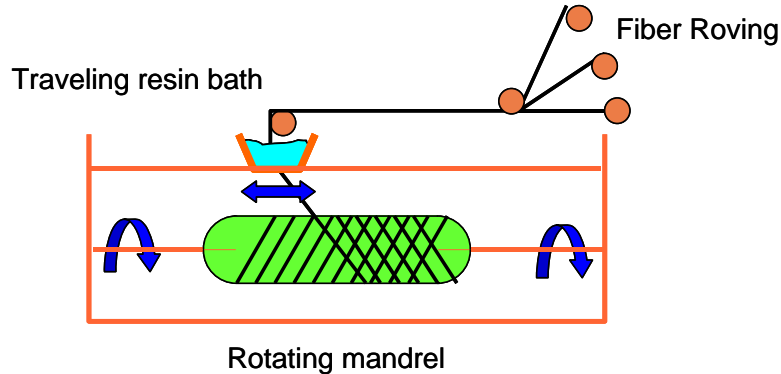
*Pultrusion* (Figure 2.2) – in this process, continuous fibers or mats are pulled through a die to form a shape having a constant cross section. Prior to entering the forming die, fibers are immersed in a resin bath to achieve fiber impregnation. The forming die is typically heated to achieve curing of the composite when traveling within the die. Therefore, pulling speed is a fundamental parameter that needs to be controlled in this process to achieve full curing and impregnation of the composite.



**Figure 2.2 – Schematic of pultrusion fabrication process**

*Filament Winding* (Figure 2.3) – the filament winding process is commonly used to fabricate hollow cylindrical objects such as pipes, tanks, posts, etc. Fibers are pulled into a traveling resin bath that is positioned according to the fiber location along the object being fabricated. Fibers are then wound onto a rotating mandrel where the object

mold is attached. Fiber orientation is controlled by mandrel rotation speed relative to traveling speed of resin bath and fiber delivery mechanism.



**Figure 2.3 – Illustration of filament winding machine** (adapted from Hollaway and Head 2001)

*Resin Transfer Molding* – preformed fiber is applied onto a mold and encapsulated within a vacuum bag. The fiber mat is then impregnated by injecting resin into the mold. The resin injection process must achieve complete fiber impregnation and eliminate all voids in the formed composite. Various processes are available to inject the polymer resin into the mold, including vacuum assisted resin transfer molding (VARTM), thermal expansion resin transfer molding (TERTM), or resin infusion (Hollaway and Head 2001).

*Compression Molding* – composites are formed by placing fibers impregnated in resin onto a female mold and applying pressure using a male mold to eliminate any excess resin from the ACM. Compression molding is useful for fabrication of open sections, such as boat hulls.

## **2.2 Use of Advanced Composite Materials for Structural Applications in the Transportation Infrastructure**

In this report, the use of advanced composite materials (ACMs) for structural applications refers to cases where the materials are used in the primary structural system of bridges and other structures that comprise the transportation infrastructure. These materials have been used for over 15 years to rehabilitate structurally deficient or damaged structural components, such as columns or girders in bridges, in the form of jackets or externally applied fiber-reinforced plates or sheets. As a result of their adequate structural performance, their application has expanded in recent years to rehabilitate other components of the transportation infrastructure.

In new construction, ACMs have been used in bridge decks as the main load carrying structural components or as internal reinforcement for reinforced concrete decks. This section presents a summary of the most common types of applications of ACMs in main structural components of the transportation infrastructure.

### ***2.2.1 Rehabilitation of Existing Structures***

The first use of ACMs in the transportation infrastructure was in the area of rehabilitation of existing structural components. Glass and carbon fiber-reinforced jackets have been used extensively in California to confine structurally deficient reinforced concrete columns and improve their performance in future earthquakes (Figure 2.4 and Figure 2.5). Many states have used externally bonded FRP sheets to strengthen or repair components of bridges (Florida, Texas [Figure 2.6], Ohio).



**Figure 2.4 – Column rehabilitation using automated filament winding machine**  
(source: FHWA)



**Figure 2.5 – Column rehabilitation applying FRP sheets using hand layup procedure**  
(source: FHWA)



**Figure 2.6 – Flexural strengthening of bridge joists using pultruded CFRP plates**  
(Brena and Steves 2003)

Advanced composite materials have been also used recently in the rehabilitation of underwater structures. For example, concrete piles in the passenger ship terminal at the port of New York were encapsulated with prefabricated glass fiber-reinforced sleeves. The annular space between the existing piles and the GFRP sleeve was filled with an epoxy-aggregate mixture pumped underwater into position (Williams 2006). Water-activated epoxies have recently been used in rehabilitation of underwater bridge substructures (Mullins et al. 2006). Glass and carbon composite jackets were formed in place by hand layup using resin-impregnated mats that were sealed in hermetically tight packages prior to arrival to the site to avoid initiating the curing process. These last two application examples are meant only to illustrate the versatility and constant developments occurring in the advanced composites industries.

### ***2.2.2 Internal Reinforcement of Concrete Components***

Advanced composite materials have also been used to fabricate internal reinforcement of concrete components to avoid problems associated with corrosion of steel reinforcing bars. A large variety of reinforcing products fabricated using ACM exist in the market including reinforcing bars, reinforcing mats, and prestressing strands fabricated using glass, carbon, or aramid fibers in combination with various polymer resins (Figure 2.7).



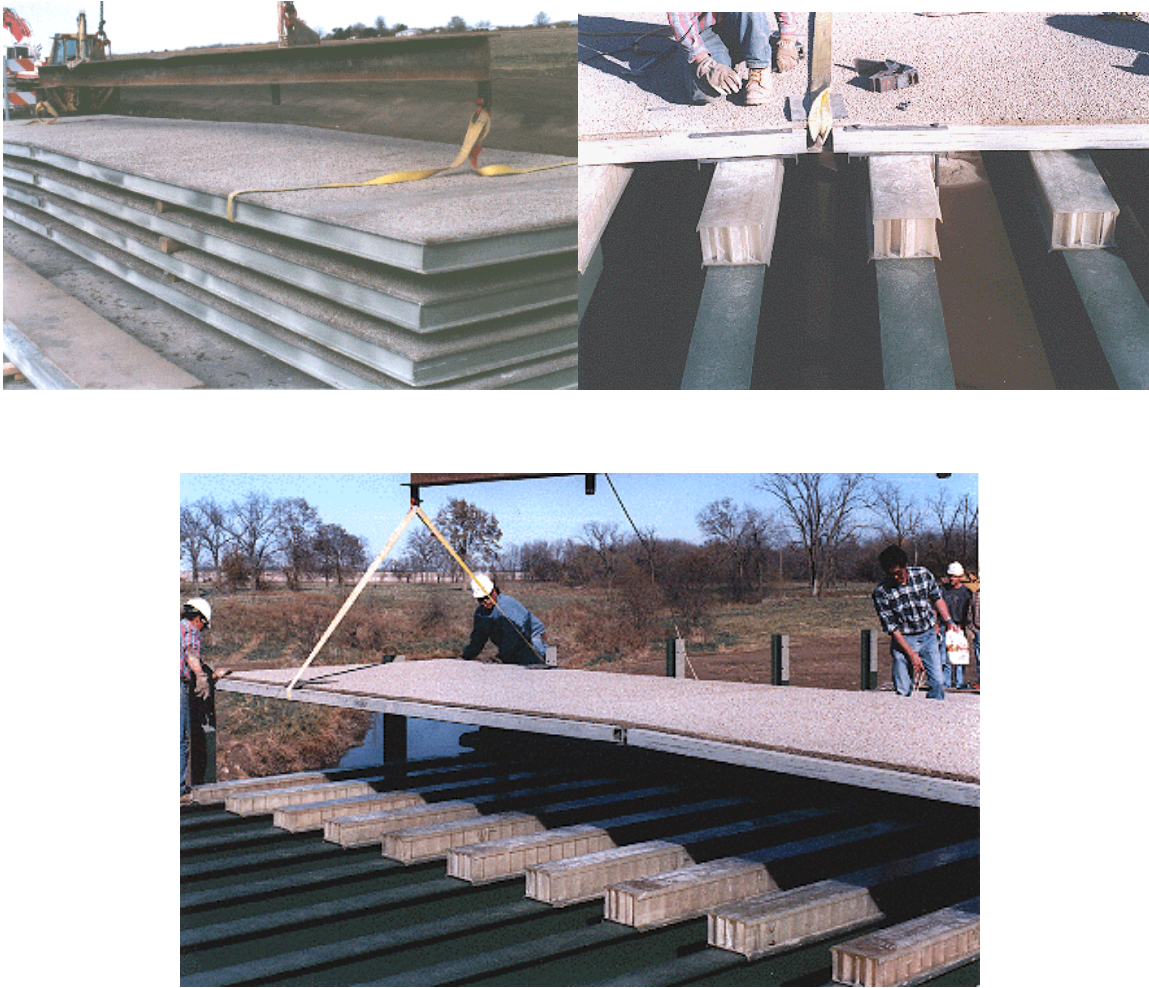
**Figure 2.7 – Examples of existing types of FRP reinforcing bars and mats**

Bridge decks and crash barriers are the two most common types of structural concrete members where steel reinforcement has been replaced by some form of FRP reinforcement. These two types of members are often in contact with de-icing chemicals, which cause severe corrosion of steel reinforcement after a limited number of years in service. FRP reinforcing bars have been used in these applications to eliminate problems with corrosion of internal reinforcing steel and extend the service life of these infrastructure components. FRP bars have been used to replace the top steel reinforcing mat in several bridge decks in the United States, for example in Ohio (Huckelbridge and Eitel 2003), Texas (Bradberry and Wallace 2003), Virginia (Phillips et al. 2005), Wisconsin (Berg et al. 2004); West Virginia (Hanna 2003); and Quebec, Canada (Benmokrane et al. 2004), and as full replacement of deck reinforcement in only a few cases such as the Rollins Road Bridge in New Hampshire and the Morristown Bridge in Vermont (see Chapter 4).

### **2.2.3 Composite Material Decks**

Advanced composite materials have also been used to fabricate bridge decks. Some advantages that these materials offer compared with traditional construction materials are: (1) lightweight products compared with concrete decks, which can simplify construction and reduce substructure costs; (2) modularity that can translate into a shorter construction schedule; (3) chemical attack resistance, particularly with reference to de-icing salts; and (4) fatigue resistance. An excellent summary of the current practice on the use of FRP decks and superstructures can be found online at [www.fhwa.dot.gov/bridge/frp/deckprac.htm](http://www.fhwa.dot.gov/bridge/frp/deckprac.htm).

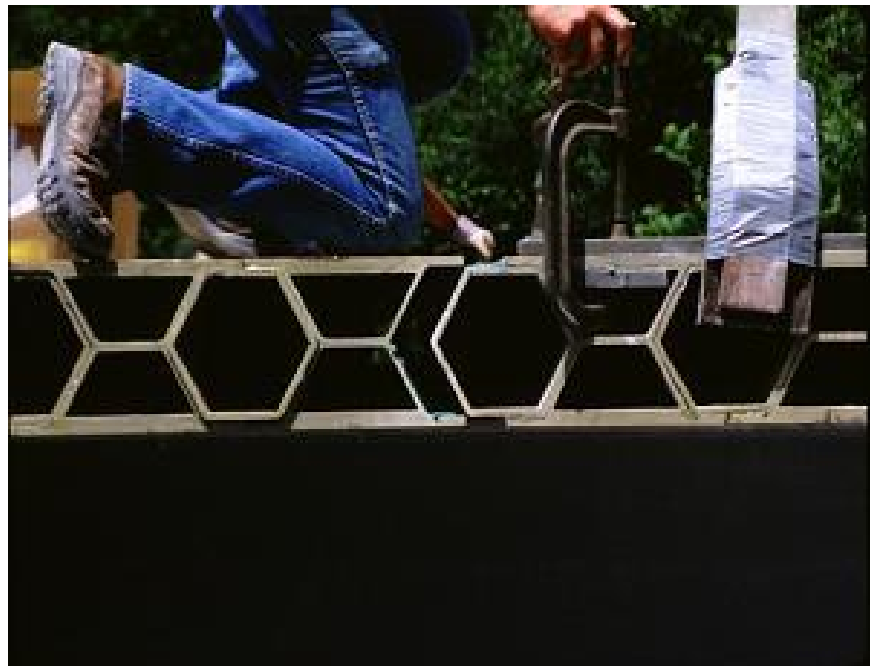
Different manufacturers in the United States have produced several deck designs. A wearing surface is sometimes integrated to the deck at the manufacturing facility reducing the number of construction operations required on-site. As Figure 2.8 through Figure 2.13 illustrate, many different structural shapes have been fabricated and used as bridge deck components.



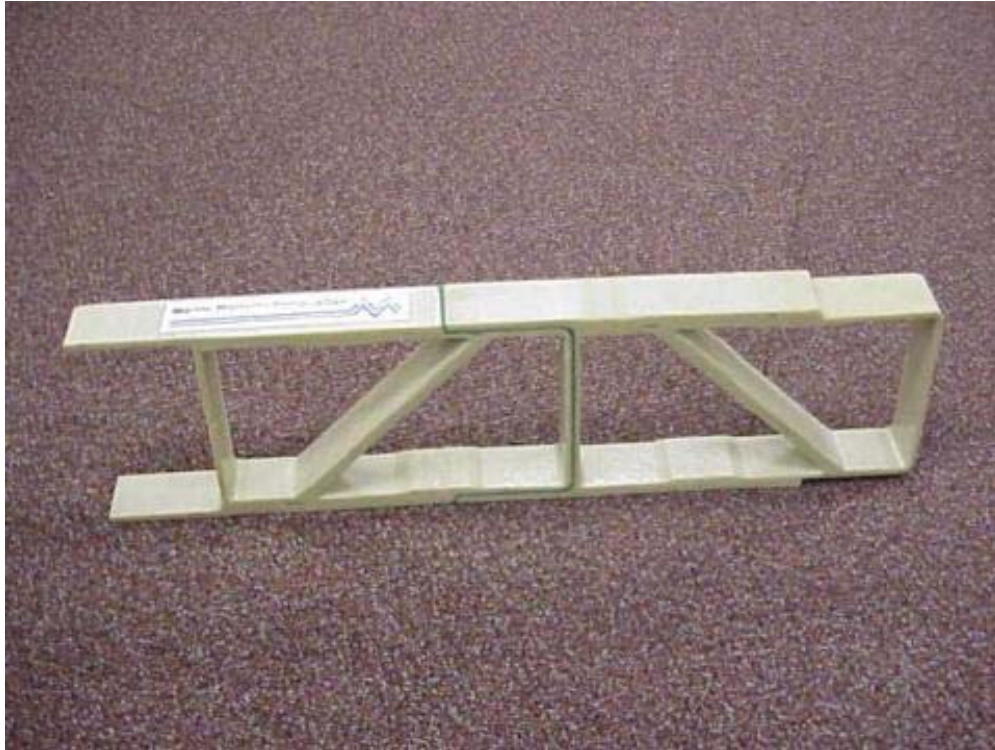
**Figure 2.8 – FRP decks** (Kansas Structural Composites, Inc., source: FHWA)



**Figure 2.9 – Honeycomb deck – Kansas Structural Composites, Inc. (source: FHWA)**



**Figure 2.10 – Creative pultrusions deck (source: FHWA)**



**Figure 2.11 – Bridge deck produced by Martin-Marietta<sup>1</sup> (source: FHWA)**



**Figure 2.12 – Different bridge deck sections (4 in. and 8 in. deep) manufactured by Bedford Plastics**

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<sup>1</sup> At the time of writing this report (May 2006), Martin-Marietta had ceased production of bridge deck products (Duraspan<sup>®</sup>) for a period of at least 12 months.



**Figure 2.13 – Structural shapes produced by Strongwell for use in bridge decks**

#### **2.2.4 Composite Piles**

Piles fabricated using ACMs have been used for load-bearing purposes and as sheet piles in marine applications. Hollow shapes filled with concrete are gaining popularity for load bearing applications, in particular where piles are subjected to either sulfate or chloride attack. Concrete filled fiber-reinforced tubes have been used for marine piles or as support of bridge piers (Fam, Greene, and Rizkalla 2003; Pando et al. 2003).

Sheet piles fabricated using GFRP materials have also been used in marine applications. These sheet piles can be driven using common pile-driving equipment (impact or vibrating hammers). Proprietary GFRP systems are currently fabricated by pultrusion in the United States, such as the SuperLoc<sup>TM</sup> composite sheet pile ([www.creativepultrusions.com](http://www.creativepultrusions.com)).

### **2.3 Use of Advanced Composite Materials for Non-Structural Applications in the Transportation Infrastructure**

Section 2.2 illustrates areas where ACMs have primarily been used in the transportation infrastructure as revealed from the literature review conducted for this project. The applications described in that section were termed *structural* because failure of those components could potentially generate a life-safety condition. Widespread use of ACMs in these areas has been impaired because of the concern that engineers have of their long-term performance under the loading conditions encountered in transportation structures. This section presents applications that do not compromise the structural

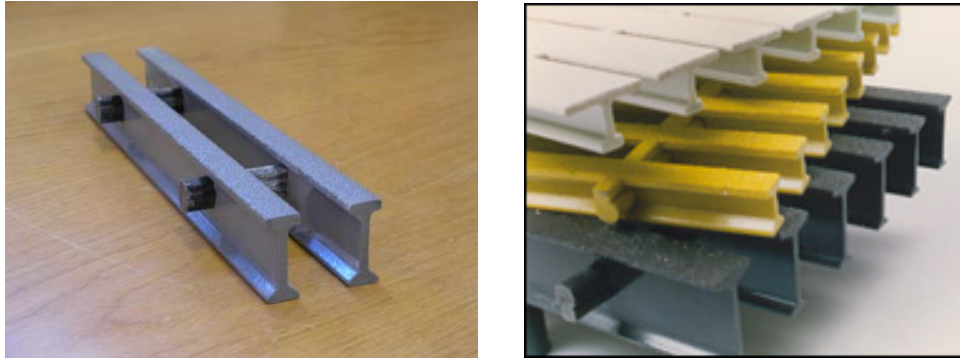
integrity of the transportation network, where ACMs might be used as alternative to traditional construction materials. For this reason, the applications presented in this section are termed *non-structural* although it is recognized that the composite materials provide the structural integrity of the individual components fabricated through their use.

There are currently a large number of ACM product fabricators that specialize in different products and fabrication methods. A large listing of ACM product fabricators and their product lines can be found at [www.compositesworld.com](http://www.compositesworld.com). Some representative ACM products in the non-structural category that have been fabricated and can potentially be used for transportation infrastructure applications include:

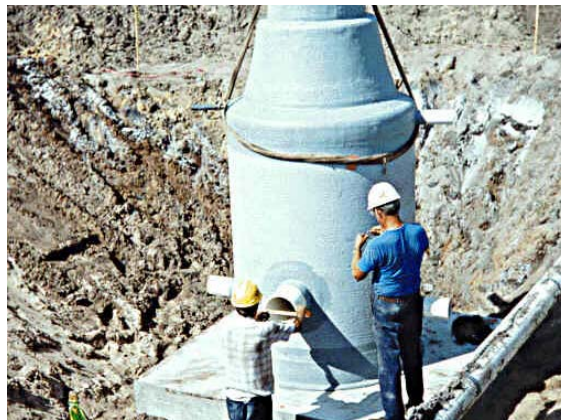
- Culverts
- Drains, trenches (Figure 2.14)
- Grating (Figure 2.15)
- Guardrails/Bridge railing
- Manholes, manhole covers (Figure 2.16)
- Signs
- Sign posts (Figure 2.17)
- Sound barriers (Figure 2.18)



**Figure 2.14 – Use of ACMs for drain and trench fabrication** (trench photograph courtesy of Strongwell)



**Figure 2.15 – Samples of grating products: Duradek® (Strongwell) and Supergrate™ (Creative Pultrusions)**



**Figure 2.16 – Single-piece glass fiber-reinforced manhole** (source: L.F. Manufacturing, Inc., East Giddings, TX)



**Figure 2.17 – Glass fiber-reinforced sign post** (source: Highway Composites, Big Springs, TX )



**Figure 2.18 – Sound barrier fabricated from post-consumer recycled plastics – EverQuiet Wall™** (photograph courtesy of William Marcussen, New Frontier Industries, NH)

### **3. Current State on the Use of Advanced Composite Materials in New England**

The main goals of this research project were to evaluate the state of practice and use of ACMs in the transportation infrastructure in New England and to identify potential steps that could be taken to increase the use of these materials within this sector. In this regard, it was considered important to incorporate viewpoints from the perspective of the three main groups (researchers, fabricators, and DOT users) that contribute to the state of the technology and its practical implementation.

Three different tools were used to evaluate the current state of practice and use of ACMs within New England: (1) conducting a literature review, (2) preparing and sending questionnaires to two different groups, and (3) conducting meetings with DOT engineers and composite material manufacturers. An extensive literature review to evaluate the state-of-the-art in research and practice in composites materials use in transportation infrastructure applications primarily within the United States was conducted. This literature review was conducted using different library databases and web-based searches. Identification of relevant journal papers, magazine articles, and web pages yielded information on current research efforts, field applications of composites, and composite material manufacturers, respectively.

#### **3.1 Questionnaires**

Two different questionnaires were prepared with specific questions intended for the two main groups affecting the use of composites in the transportation infrastructure: fabricators and end users (personnel within transportation agencies in New England). A summary of responses received from these two groups is presented in Section 3.3. A copy of the two types of questionnaires is included in Appendix B.

As a first step, fabricators of advanced composite materials with operations located within New England were identified and their contact information was obtained from Web-based searches and magazines from the composite industry (e.g. [www.compositesworld.com](http://www.compositesworld.com), Composites Technology, High Performance Composites). Personnel within these companies were contacted by telephone to determine their interest in participating in future joint meetings between fabricators and transportation agency personnel. A questionnaire prepared specifically for ACM manufacturers was then sent to all companies that were identified in this effort. Questionnaires were sent electronically and responses were received by e-mail or transmitted by fax.

The goals of preparing a manufacturer-specific questionnaire were manifold. It was of interest to assess whether manufacturers had the capability to fabricate ACM products that could be used in the transportation infrastructure without any major investment or change in their production lines. Associated with production, it was of importance to evaluate whether the volumes commonly required for transportation related activity could be accommodated within their current manufacturing setup. The questionnaire was also intended to identify any previous efforts that fabricators had

undertaken to participate in the transportation infrastructure sector. Fabricators were also asked to identify their main products and the industry sector for which these products were primarily fabricated. The questionnaires also served to identify other companies in New England that could be contacted for feedback by having collaborated with manufacturers that were originally contacted.

Engineers in transportation agencies were also contacted to respond to a questionnaire. The DOT-specific questionnaires had the primary goal of identifying the experience of personnel within transportation agencies in New England with the use of ACMs. This questionnaire was also used to identify companies that had participated in the past in transportation infrastructure projects. It was also paramount to evaluate if the experience with the use of ACMs had been positive and whether there had been any problems during the implementation of the technology in each particular project. The next section presents a summary of responses received from engineers and fabricators.

### ***3.1.1 Summary of Questionnaire Responses***

Questionnaires were sent to transportation agencies in the six New England states and to all the fabricators indicated in Appendix A. Eight responses were received from engineers at transportation agencies (at least one for each state, Table 3.1) and fourteen fabricators responded to the questionnaires (see Appendix A).

**Table 3.1 – Questionnaire responses from DOT engineers**

<b>State</b>	<b>No. of responses</b>	<b>Familiarity with ACMs</b>	<b>Previously used ACMs in projects</b>
Connecticut (CT)	2	Very	Yes
Massachusetts (MA)	1	Somewhat	No
Maine (ME)	2	Very	Yes
New Hampshire (NH)	1	Very	Yes
Rhode Island (RI)	1	Very	Yes
Vermont (VT)	1	Very	Yes

All but one of the respondents from the DOT group considered themselves *very familiar* with ACMs, indicating that they knew about basic properties of the materials and some manufacturing processes. A response marked as *somewhat familiar* indicated knowledge on applications but limited knowledge on limitations of materials and composition (material components). All states indicated prior experience on use of ACMs in previous projects, primarily funded through the FHWA-funded *Innovative Bridge Research and Construction* (IBRC) program. A summary of the projects where ACMs have either been used or been considered for use in the state DOTs is listed in Table 3.2. Details of the applications that proceeded to project completion are presented in Chapter 4. Finally, Table 3.3 lists the concerns that engineers had on using ACMs in future projects and potential areas where use of these materials in transportation infrastructure applications was considered viable.

**Table 3.2 – Use of ACMs in prior transportation infrastructure projects**

State	Reason for using ACMs	Problems to date	Project
CT	Lightweight	None	Deck panels/Sidewalks Bridge inspection platform.
MA	—	—	—
ME	Cost effective alternative, lightweight materials, to monitor life expectancy of GFRP materials, to reduce need of prestressing steel tendons	Performing as expected in all projects; lower prestress loss in service	Several bridge and pier replacements, GFRP reinforced girders with glulam deck, stress laminated timber bridge prestressed with 12-0.5" diameter GFRP tendons, vertically laminated glulam panels, FRP docks
NH	Research	Material too costly	CFRP NEFMAC reinforcing grid
RI	Seal pier cap to prevent chloride entry	Water appears to be entering from top of pier cap	Pier cap wrapping
VT	Resistant to de-icing salts	None (satisfactory after 1 year)	GFRP bars in bridge deck

**Table 3.3 – Concerns on use and future uses of ACMs**

State	General concerns on use of ACMs	Potential future uses of ACMs
CT	Fatigue behavior, repair, UV performance, lack of familiarity with material	Pedestrian bridges, sidewalks on bridges, wrapping columns, drainage spouts, handholes
MA	Lack of design guidelines and specifications	Timber replacement
ME	Lack of design code, initial costs, long-term durability in evaluation	FRP bridge drains (being currently used), sign posts, guard rails, all FRP decking in historical trusses (lightweight needs), movable bridges, temporary bridge deck panels, FRP docks, FRP pilings
NH	Cost	Prefab rail shapes if brittle nature can be overcome
RI	Durability, resistance to sunlight	
VT	Long term behavior, lack of design codes, UV degradation	Bridge decks (vehicular and pedestrian), bridge rehab projects when lightweight is needed

Of the fourteen responses received from fabricators of ACM products, ten indicated being very interested in participating with DOT engineers in future projects, three responded as not being interested, and one was undecided. They indicated being capable of producing a wide variety of products using different fabrication methods, including resin transfer molding, filament winding, custom molding, and hand-layup techniques. They also indicated being able to adapt their current manufacturing facilities to accommodate production of items required for transportation infrastructure applications. Five fabricators indicated having participated previously in transportation related projects, with fabrication of products such as GFRP rods, bridge parts (did not specify the parts), rail cars, manhole inverts, automotive components, piping, FRP repair forms, FRP reinforced wood piles, prototype guardrails, prototype pile casing. From the questionnaire responses received from ACM product fabricators, the main obstacles they perceived for wider use of ACMs in transportation infrastructure projects were current bridge design codes, conservative approval policies adopted in state DOTs, uncertainty of payback for development efforts, and willingness of engineers to use products in their designs. A more detailed discussion of perceived obstacles from the perspective of fabricators and DOT engineers is presented in sections 3.3.1 and 3.3.2, respectively.

### **3.2 Meetings at State DOTs and Transportation Agencies**

Four meetings were held throughout New England to present project findings and receive feedback from the engineers' perspective on the use of ACMs for transportation infrastructure projects. Meetings were held at MassHighway (January 2005), New Hampshire DOT (June 2005), Vermont Agency of Transportation (August 2005), and Connecticut DOT (November 2005). Additionally project findings were presented at the AASHTO Bridge Sub-committee Meeting (Committee T6 – Technical Committee for Fiber-Reinforced Polymer Composites) held in Rhode Island in June 2005. The participants in these meetings mostly included engineers from the host state DOT, but also included representatives from three different composites manufacturing companies in the meeting at the NH-DOT. Also, two videoconferences were held within the duration of the project to update the technical oversight committee on project achievements.

### **3.3 Perceived Obstacles on Wider Use of ACM Materials in Transportation Infrastructure Projects**

Perceived obstacles on the wider use and acceptance of composite materials in the transportation infrastructure were identified from the perspective of ACM manufacturers (producers) and from engineers in transportation agencies (end users). The three main sources used to collect this information were the comments received in returned questionnaires from fabricators and DOT engineers, individual telephone conversations with these individuals, and comments voiced during project meetings. The major obstacles that were identified through this process are discussed in the following sections. Obstacles that were identified by fabricators and end users alike are:

- High initial cost of materials

- Lack of design provisions
- Limited track record in Civil Engineering
- Environmental concerns (recycling)
- Insufficient knowledge of long-term performance of FRP products
- Lack of availability of inspection procedures to assess long-term performance
- Little familiarity of engineers with composite material behavior

### ***3.3.1 Perceived Obstacles - Producers' Perspective***

All producers that responded to the questionnaires indicated that they were interested in participating with transportation agencies in the future. Some have already established contacts and have an established collaboration with their state Department of Transportation in transportation infrastructure projects (e.g. Kenway Corp., Augusta, ME).

Several producers believed that the higher initial cost of composite materials was the main reason for their limited use in transportation infrastructure applications. Although the cost of composite materials has decreased during the last few years and cost of traditional materials (e.g. steel) has increased, fiber-reinforced products are still more costly to fabricate than products made from traditional construction materials (wood, steel, aluminum, or concrete). An important aspect worthy of highlighting is that all comments received related to the economic implications of using composite materials referred only to first-cost without regard to the reportedly improved long-term durability performance of composite materials compared with other construction materials. Manufacturers indicated that some products, however, could be fabricated very competitively in comparison with traditional construction materials. Improvements in production methods of elements consisting primarily of flat surfaces or elements fabricated using filament winding techniques (pipes) were listed as examples of products that can be currently produced cost-competitively. These products can be used in signage and drains, respectively, in transportation infrastructure projects.

ACM producers expressed concern about the cost implications of modifying their production capabilities without receiving significant payback. Because fabrication techniques of composite material products vary significantly, a major equipment and space investment is required if manufacturing facilities are expanded to include other fabrication processes. For example, the equipment required to produce elements fabricated using resin-transfer molding techniques is completely different from that necessary to produce pultruded shapes. Pultrusion requires more space and a continuous production line while the space for RTM is highly dependent on the size of product being manufactured.

On the design aspect, several fabricators viewed current design documents used in transportation infrastructure projects as prescriptive and very conservative in nature. They identified the language and the way design codes are structured as an obstacle to the wider use of ACMs in the transportation infrastructure. Because the physical and mechanical properties of ACMs can vary significantly depending on the constituent materials and fiber orientation, producers are used to designing their products to satisfy specific performance requirements specified by clients. ACM manufacturers were not certain they understood what the performance requirements are for transportation infrastructure projects. They believe that better communication with engineers at state DOTs would definitely allow identification of specific performance characteristics that a particular product must satisfy.

Finally, some fabricators expressed concerns about combined environmental effects that are encountered commonly in highways within New England. There is a lack of information on the performance of ACM under the combined environmental effects that they would encounter if used in highways. The presence of moisture or freeze-thaw cycles in combination with de-icing salts was of particular concern. A research project sponsored by the National Cooperative Highway Research Program (NCHRP) to investigate the performance of bonded composite materials used for concrete beams strengthening under combined environmental effects is ongoing at the time of this writing (*NCHRP Project 12-73: Design Guidelines for Durability of Bonded CFRP Repair/Strengthening of Concrete Beams*). The findings from this project will likely provide critical information needed in this area.

### ***3.3.2 Perceived Obstacles - End Users' Perspective***

Concerns of engineers at state transportation agencies and DOTs about the use of ACMs in the transportation infrastructure can be broadly classified into the five main categories discussed below.

#### **a) Material related concerns**

*Large variety of composite materials* – Engineers expressed concerns about large variety of resins and fibers and lack of transparency in the production of specific materials. Laboratories in transportation agencies are not currently equipped to conduct material tests required to ensure the quality of composite materials received for a project. Engineers have had to rely on the mechanical properties of composite materials provided by the manufacturers to design components used in the limited number of projects that have used ACMs in New England (see Chapter 4). In some cases engineers reported not being able to determine the material received for a project and were concerned about their inability to calculate the strength of a component. Manufacturers have immediate access to the constituents making up a composite material (type of resin, type of fibers, fiber architecture, and number of plies) but do not necessarily report the mechanical properties needed to calculate strength of a component. Civil engineers do not commonly receive specific education on design using composite materials as part of the undergraduate curriculum. Without this knowledge, determining expected mechanical properties solely from the constituent materials and their proportions is impossible.

*Impact and brittleness of composite materials* – It is well known that the stress-strain behavior of composite materials is linear to failure in contrast with steel that exhibits a well-defined yield point. This material characteristic has concerned engineers because of the perceived reduced deformation capacity of composite materials compared with that of steel. Additionally, some engineers were concerned about material brittle behavior under impact, in particular at low temperatures occurring during winter.

*Long-term material behavior* – The durability of composite materials has been questioned in recent years, in particular under the combined effects of various potentially deleterious agents. No information is yet available of the effects of moist environments or low-temperature environments in combination with de-icing salts. Concerns exist on the potential for degradation of physical and mechanical properties of composite materials in these combined environmental conditions. In alkaline environments or under ultraviolet exposure, degradation of glass fiber-reinforced composites has been reported. This has caused some concern among engineers about the long-term durability of these composite materials used as internal reinforcement for concrete.

*Thermal properties and fire resistance* – engineers expressed concern on aspects related to degradation of mechanical properties and dimensional stability of composites at high temperatures. All polymers soften, decompose, or both at elevated temperatures (Hollaway and Head 2001). The critical temperature when thermosetting polymers start to lose stiffness is known as the glass transition temperature ( $T_g$ ). The glass transition temperature varies depending on the polymer composition. Thermosetting polymers most commonly used in civil engineering applications (epoxy, vinylester, polyester) begin to break down and weaken at around 200°C (Hollaway and Head 2001). Creep of polymeric materials commonly increases at higher temperatures, even at temperatures well below the  $T_g$ . However, creep in thermosetting advanced composite materials is not as pronounced as it is in thermoplastic materials.

Ignition properties of composite materials vary depending on the type of polymer used and its thermal stability. Incorporating additives in the polymer composite formulation can enhance fire resistance of composites. At present, the behavior of composites under fire conditions (fire spread, fire resistance) is not well understood. Current research at the Worcester Polytechnic Institute – Fire Protection Engineering Department (Prof. Nicholas Dembsey) will provide valuable information in this topic.

*Material recycling* – there were concerns raised about the ability to recycle ACMs after reaching the design life of a given component, and their future environmental impact. Because of the large variety of fibers and resins that can be used to fabricate ACMs, a general procedure to recycle these materials does not exist. The cross-linking process that takes place during curing of resin is not reversible. Therefore neither chemical agents nor high temperatures can be used to recycle resin to form new resins. As a consequence, fibers embedded in polymers are difficult to extract for recycling and the formed composite has to be recycled as a unit. Mechanical procedures (shredding) might be used in the future as a recycling avenue for fiber-reinforced composites for other civil engineering applications such as fills, concrete aggregates, etc.

b) Design concerns

*Lack of design documents* – the general consensus was that little design guidance existed for ACMs. Existing projects that have incorporated ACMs were designed adapting current AASHTO design procedures to composites. This practice is not viewed as the most desirable one, and a need for material-specific design guidelines was expressed by engineers at all state DOTs and transportation agencies. Particular concern was expressed on procedures to connect different FRP materials (bearing, friction, adhesive, or combinations), and to material specific resistance factors to account for brittle behavior of composite materials.

In many cases, manufacturers of composite materials provide design services for their own products. A number of product-specific design manuals (e.g. Strongwell Design Manual, Bedford Plastics) currently exist. DOT engineers indicated that manufacturer designs should be open for peer review, which ideally would be done at the transportation agency. A mechanism should be proposed to achieve a desirable peer review process when designing using composite materials.

Engineers felt that given the current state of knowledge ACMs should only be used as secondary elements (non-structural), not as the primary load-resisting elements because of lack of knowledge of design/performance. Structural strengthening applications or use as protective coatings to increase durability of traditional materials were considered appropriate applications of ACMs in the transportation infrastructure.

A number of design documents for composite material applications were published by independent agencies throughout the duration of the project. These documents were not available when the project first started, so engineers had not had any exposure or opportunity to use these documents in an actual design situation. The following list includes documents that are now available and will potentially affect the practice of designing and specifying ACMs in transportation infrastructure applications:

- ACI Committee 440 (2002): *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures* – includes construction requirements and recommendations for design of FRP-based flexural, shear, and axial load strengthening techniques for concrete structures.
- ACI Committee 440 (2003). *Guide for the Design and Construction of Concrete Reinforced with FRP Bars* – provides material properties, construction practices, and design recommendations for concrete structures designed using internal FRP reinforcing bars.
- ACI Committee 440 (2004b): *Prestressing Concrete Structures with FRP Tendons* – describes available FRP tendons, provides design recommendations for concrete elements prestressed using internal or external FRP tendons.

- Canadian Standards Association (2002): *Design and Construction of Building Components with Fibre-Reinforced Polymers* – contains provisions for design of FRP bars in concrete construction, provisions for externally bonded applications to strengthen existing reinforced concrete elements, and provisions for FRP composite cladding.

c) Construction concerns

*Quality control procedures* – lack of knowledge of quality control procedures for composite materials were a concern to engineers in transportation agencies. Engineers are largely unfamiliar with accepted testing protocols for composite materials. Additionally, it was believed that existing testing capabilities would need to be expanded to be able to test composite materials for specification compliance. It was difficult to envision how engineers in the materials testing groups within transportation agencies could guarantee if products met specifications. Proprietary systems, in particular, pose a challenge because the resin and fibers formulation would not be available for testing. Questions arose on whether manufacturers would provide internal test reports on material coupons prepared with the same formulation of resin and fiber content, similar mill test reports that steel manufacturers provide for steel heats. It also was not clear if common tensile, compressive, or shear tests on material samples provided sufficient information on material properties to guarantee performance in the field. ACI Committee 440 prepared document *ACI 440.3R-04: Guide Test Methods for Fiber-Reinforced Polymers (FRP) for Reinforcing or Strengthening Concrete Structures* to address concerns that engineers had on test methods (short and long-term) available for FRP products commonly used in concrete construction. The document describes test methods that can be used by engineers to ensure that a given product satisfies project specifications.

*Damage during handling* – concern was expressed about damage occurring during handling composite material products in the field. Micro cracking of material might go undetected and could evolve into macro cracks because of the brittle nature of materials. Engineers indicated a need to develop inspection techniques to assess damage to composite material components in the field. *NCHRP Report 514: Bonded Repair and Retrofit of Concrete Structures Using FRP Composites – Recommended Construction Specifications and Process Control Manual* (TRB 2004) provides guidance on aspects related to inspection, storage, and handling techniques of composite materials used in externally bonded applications. This document could be used as a starting point to develop guidelines for handling and storage for other types of FRP products used in construction projects.

*Reinforcing bar bendability* – existing applications of fiber-reinforced bars in reinforced concrete construction have been limited to cases where straight bars were used. This is a result of the lack of availability of procedures to bend FRP bars in the field and engineers expressed this as an obstacle for wider use of composites in this particular type of application. This need has also been identified by researchers in recent workshops (Porter and Harries 2005) and is something that will probably be addressed in the near future.

(d) Contractual (bidding) concerns

Issues related to contractual and bidding process of public projects that were raised during project meetings are summarized in this section. In many cases projects are awarded based on a lowest-bid criterion. It is well known that ACMs are more costly than traditional construction materials and are impossible to justify on a first-cost basis exclusively. Engineers expressed that DOTs were able to justify a higher initial cost (in cases up to twice the lowest cost of an equivalent product) if it would translate into long-term savings due to reduced maintenance and replacement costs over the years.

Several ACM manufacturers produce materials fabricated using either proprietary processes or resin-fiber systems. Proprietary systems are difficult (if not impossible) to specify in state projects. Whenever construction specifications call for a specific product, they must include a statement indicating that an equivalent product may be used instead. It is difficult to specify product equivalents in the case of proprietary systems because of lack of general knowledge of material composition. A possible solution might be to specify the product-equivalent by specifying desired performance, but current state contracts are not written this way.

Prequalification of ACM products for transportation infrastructure projects was not perceived feasible at this time. The first step in achieving prequalification is to develop standard specifications of the materials and these have not been developed for use in civil engineering applications. Development of standard specifications is impossible without accepted design and material testing procedures. The fact that these materials are often developed using proprietary resin formulations, proprietary fiber sizing, etc. imposes another hurdle in standardization of the products.

(e) Maintenance concerns

Because of the limited use of ACMs in transportation infrastructure projects, maintenance and inspection crews are not familiar with the materials. These crews are trained to quickly detect damage to traditional civil engineering materials and make an assessment of need for repair based on visual observations of the damage. In the case of ACMs, visual indications of damage might be hard to accomplish. This concern must be addressed through an adaptation of inspection procedures for the use of these new materials. Techniques available to repair damaged components need to be addressed. Even though industry experts indicate ease of repair as a potential benefit that ACMs have over conventional materials, maintenance crews need to be trained on techniques through which repair of ACMs can be achieved.

As mentioned before, one of the major applications of ACMs in transportation infrastructure system components is for repair of damaged or deteriorating structural elements due to corrosion. Full encasement in FRP jackets is not an uncommon practice, after which the condition of the original element is not visible after repair. This posed a major concern among engineers in transportation agencies since visual inspection techniques can no longer be used to assess the condition of the original structural element. Non-destructive techniques might provide a useful assessment tool in this case.

## **4. Applications of Advanced Composite Materials in New England**

### **4.1 Main Reasons for Using FRP Materials**

As discussed in Chapter 3, end users identified a series of impediments for the wider use of composite materials in transportation infrastructure projects. A number of applications, however, currently exist within New England that illustrate a wide variety of opportunities for the use of these materials in future projects. Engineers indicated that the main reasons that ACMs were selected for the projects detailed in this chapter are:

- Light weight (replacement of deteriorated decks in older bridges designed under old design loading)
- Investigating use of new material and avoid deterioration observed in existing infrastructure
- Repair of damaged or deteriorated infrastructure (cracking, spalling)
- Pre-manufactured pedestrian bridges are perceived as a potentially good application (small equipment required for construction).

The following sections provide details of projects where ACMs have been used across New England.

### **4.2 Applications in Connecticut**

#### ***4.2.1 Repair of Cracking in Tubular Connections of Overhead Sign***

Inspection of overhead signs constructed using aluminum tubes has revealed cracking at the welded joints in some cases. To repair these cracks ACMs consisting of glass and carbon fiber-reinforced jackets have been used in Connecticut in sign # 21150 located over Interstate Highway I-84 above the on-ramp in exit #36 (Slater Road – New Britain, CT). The repair took place in June 2005 and has been inspected periodically. So far the composite jackets have exhibited little change in appearance after 4 months in service and no signs of cracking or debonding has been observed. Several photographs of the two repaired joints taken during a field inspection in October 2005 are shown in Figure 4.1 through Figure 4.4.



**Figure 4.1 – Glass FRP jacket at bracing connection of overhead sign above left lane**  
(Photograph courtesy of Ned Statchen, Conn-DOT)



**Figure 4.2 – Picture of glass FRP jacket taken toward sign** (Photograph courtesy of Ned Statchen, Conn-DOT)



**Figure 4.3 – View of carbon FRP jacket in brace connection past the right shoulder outside the roadway** (Photograph courtesy of Ned Statchen, Conn-DOT)



**Figure 4.4 – Another view of the carbon FRP jacket in connection outside roadway** (Photograph courtesy of Ned Statchen, Conn-DOT)

#### **4.2.2 Housatonic River Bridge (Milford, CT)**

The Connecticut Department of Transportation (Conn-DOT) is currently using ACMs in CDOT Project No. 83-244, The Housatonic River Bridge in Milford, CT. ACMs are being used in a fiber-reinforced polymer (FRP) fender and pile system under the bridge. These components are fabricated by Seaward International, Inc. from Clearbrook, VA ([www.seaward.com](http://www.seaward.com)). The General Contractor for this project is Cianbro

Corp. of Pittsfield, Maine ([www.cianbro.constructware.com](http://www.cianbro.constructware.com)). The SIP Forms will be installed on concrete filled fiberglass piles and then filled with concrete.

At the time of this writing, manufacturing of the fender-pile system had not begun. FRP composite piles and fenders were chosen for their durability, resistance to marine corrosive environment, and desire to assess the performance of innovative materials under a high corrosive environment. Partial funding for this project was received from the Federal Highway Administration (FHWA) to build this project.

### **4.3 Applications in Maine**

The Maine Department of Transportation (Maine DOT), the Advanced Engineered Wood Composites Center (AEWC) at the University of Maine, the Maine Division Office of FHWA, and the composites industry in Maine have established a partnership to promote use of FRP materials in the transportation infrastructure. A major goal of this collaboration is to promote the cost-effective use of regional wood species combined with FRP materials to increase the stiffness of the fabricated structural components. Funding for demonstration projects for this technology was secured through the Innovative Bridge Research and Construction Program (IBRC) of FHWA. Products fabricated entirely using FRP materials have also been used in the transportation infrastructure (deck drains, docks). Examples of these applications are listed below.

#### **4.3.1 Skidmore Bridge**

The Skidmore Bridge crosses the Medomak River between the towns of Washington and Union in Maine. The original bridge needed replacement because of deterioration that had occurred over the years (Figure 4.5). The superstructure of the replacement bridge consists of four steel girders with FRP-glue laminated (FRP-glulam) deck panels placed in the transverse direction. The bridge has a single 56 ft. span and is simply supported on each bridge abutment. The FRP-glulam panels are 24 ft. long by 4 ft. wide. The panels are encased in a 0.15 in. thick FRP laminate that was applied after construction of the glulam panels at the facilities of the industrial partner of the project (Kenway Corp. - Augusta, Maine). Application and impregnation of the FRP reinforcement was conducted using a vacuum bagging method (Figure 4.6). Because of their light weight, each panel covering the entire bridge width could be installed using a front loader instead of a crane (Figure 4.7). This bridge alternative was compared with three other traditional bridge construction alternatives. The use of FRP-glulam decking resulted in a maximum of 13% higher initial costs than alternatives including traditional materials. A side-view photograph of the Skidmore Bridge after construction was completed is shown in Figure 4.8.



**Figure 4.5 – Original condition of Skidmore Bridge before replacement** (Photograph courtesy of Dale Peabody, Maine DOT)



**Figure 4.6 – Fabrication of FRP-glulam deck panels for the Skidmore Bridge** (Photograph courtesy of Dale Peabody, Maine DOT)



**Figure 4.7 – Installation of FRP-glulam deck panels over steel girders of Skidmore Bridge (Photograph courtesy of Dale Peabody, Maine DOT)**



**Figure 4.8 – Photograph showing Skidmore Bridge after completion (Photograph courtesy of Dale Peabody, Maine DOT)**

#### 4.3.2 *Milbridge Municipal Pier*

The Milbridge Municipal Pier is used for commercial and recreational fishing purposes. The pier consists of a seven-span simply supported structure designed for HS-20 vehicular loading. Each span has four vertically laminated glulam panels reinforced using a three-ply unidirectional glass fiber-reinforced polymer (GFRP) sheet in a phenolic resin matrix (Figure 4.9). These panels are supported on conventional reinforced concrete caps. Construction of the pier proceeded efficiently by lifting the 3000 lb deck panels using a barge crane (Figure 4.10a). The lightweight panels only represent about one-third of the weight of equivalent prestressed concrete panels. The approximate cost of this alternative, at \$36 per square foot, was highly competitive with a prestressed concrete panel alternative. To evaluate the long-term performance of the GFRP laminate, a monitoring program was developed for a period of five years after construction was completed in June 2001. A photograph showing the Milbridge Municipal Pier after completion is shown in Figure 4.10b.



**Figure 4.9 – Vertically laminated glulam panels used in the Milbridge Municipal Pier** (Photograph courtesy of Dale Peabody, Maine DOT)



**Figure 4.10 – (a) Lifting of Milbridge Pier panels during construction; (b) Finished view of Milbridge Pier** (Photographs courtesy of Dale Peabody, Maine DOT)

#### **4.3.3 Local Bridge in Fairfield Biotechnical Park**

The Fairfield Biotechnical Park Bridge provides passage across the Emery Brook into the Fairfield Biotechnical Park. The structure consists of FRP-glulam girders with a composite concrete deck. The bridge has a single 72-ft. span that is simply supported on bridge abutments. Each 75-ft. long glulam girder contains a 5/8 in. thick by 40 ft. long pultruded E-glass plate bonded to its bottom and center. To generate composite action between the girders and concrete deck, steel dowel connectors were grouted into the top face of the girders during fabrication (Figure 4.11). The bridge is being monitored for a period of 3 years to evaluate its long-term performance. Several views of the bridge during construction are shown in Figure 4.12. A view of the finished bridge is presented in Figure 4.13.



**Figure 4.11 – Grouted steel dowels used to promote composite action between glulams and concrete deck in Fairfield Bridge (Photograph courtesy of Dale Peabody, Maine DOT)**



**Figure 4.12 – Views of Fairfield Bridge glulams during construction** (Photograph courtesy of Dale Peabody, Maine DOT)



**Figure 4.13 – Finished view of Fairfield Bridge** (Photograph courtesy of Dale Peabody, Maine DOT)

#### ***4.3.4 Composite Bridge Drains in Bridges in Central Maine***

Bridge steel drains often exhibit corrosion caused by de-icing chemicals used on roads. Drain corrosion may cause concrete deck cracking and an increase in the potential for corrosion of deck reinforcement. Glass fiber-reinforced polymer (GFRP) drains could potentially alleviate this problem in addition to eliminating the unsightly rust staining that occurs from corroding components (Figure 4.14). Fabrication of FRP drains has been initiated by the Maine DOT in collaboration with the University of Maine. Drains fabricated using a combination of filament winding and wet-layup techniques have been

produced and implemented in three field applications in central Maine (Figure 4.15 and Figure 4.16). Filament winding has been used economically to fabricate the drain pipe, while wet-layup is used to connect drain attachments and drain grille (Figure 4.16). Load testing of these drains was conducted in the laboratory prior to field implementation.



**Figure 4.14 – Rusting and corrosion of steel drain under bridge** (Photograph courtesy of Dale Peabody, Maine DOT)



**Figure 4.15 – Fabrication of glass fiber-reinforced drain using wet-layup procedure** (Photograph courtesy of Dale Peabody, Maine DOT)



**Figure 4.16 – View of finished drain prior to installation in bridge deck** (Photograph courtesy of Dale Peabody, Maine DOT)

#### ***4.3.5 Fiber-Reinforced Docks***

Because of the lightweight nature of advanced fiber-reinforced composite materials and their outstanding performance in corrosive environments a potential application of these materials may be in the fabrication of docks used for recreational purposes. FRP docks avoid the environmental impact and health hazard associated with the use of chromate copper arsenate (CCA) commonly used until 2003 as a pesticide to prevent wood rotting. Harbor Technologies, Inc. of Brunswick, Maine has fabricated

FRP docks successfully, which have been used by the Maine DOT for recreational docks (Figure 4.17).



**Figure 4.17 – Fiber-reinforced polymer dock for recreational purposes** (Photograph courtesy of Harbor Technologies, Inc.)

#### **4.4 Applications in Massachusetts**

##### **4.4.1 Beam Retrofit**

As reported in the *Innovative Bridge Research and Construction* (IBRC) program web site (<http://ibrc.fhwa.dot.gov>), funding was allocated to Massachusetts for a beam retrofit project involving carbon fiber-reinforced sheets of a bridge on I-495 over an MBTA railroad line. No detailed record or additional information about this project was found from individuals within MassHighway.

#### **4.5 Applications in New Hampshire**

##### **4.5.1 Column Rehabilitation – US Route 3**

Ten square columns carrying a US Route 3 bridge over the Soucook River at the Concord-Pembroke town line (project number 12035) were rehabilitated with glass fiber-reinforced polymer jackets in 1996. All columns had a cross section of 21 in. by 21 in. and were either 20' – 6" or 17' – 6" tall. The composite material selected for the project consisted of E-glass fibers embedded in an epoxy resin matrix. The project specifications specifically stated that polyester resin was unacceptable. The composite jackets were painted with a topcoat to protect against ultraviolet degradation. The manufacturer of the composite system was RJ Watson.

##### **4.5.2 Rollins Road Bridge**

The New Hampshire Department of Transportation (NHDOT) in collaboration with the University of New Hampshire (UNH) investigated the use of high performance concrete (HPC) reinforced with fiber-reinforced polymer (FRP) composite grids to

achieve corrosion and freeze-thaw resistance in bridge decks. These materials were used in the deck of the Rollins Road Bridge in Rollinsford, NH. This bridge was built to replace an old bridge with a deck on steel girder superstructure that had deteriorated significantly over the years due to corrosion induced by use of deicing chemicals compounded by cyclic freezing and thawing of the deck.

The bridge spans the Boston-Maine Railroad and Main Street in Rollinsford, NH. The bridge superstructure consists of an 8-in. reinforced concrete deck supported on New England Bulb Tee (NEBT) prestressed concrete girders. Girders in the Rollins Road bridge are simply supported over a span of 110 ft. The entire reinforcement in the deck for positive and negative bending consists of a proprietary system (NEFMAC) of carbon fiber-reinforced polymer bars formed into two-way grids with bars at different spacings. The grids were fabricated from carbon/vinylester composite bars with a reported ultimate strain of 14,000 microstrain. A modulus of elasticity of approximately 10,400 ksi was measured in the laboratory for the composite material used in this project (Bowman et al. 2003).

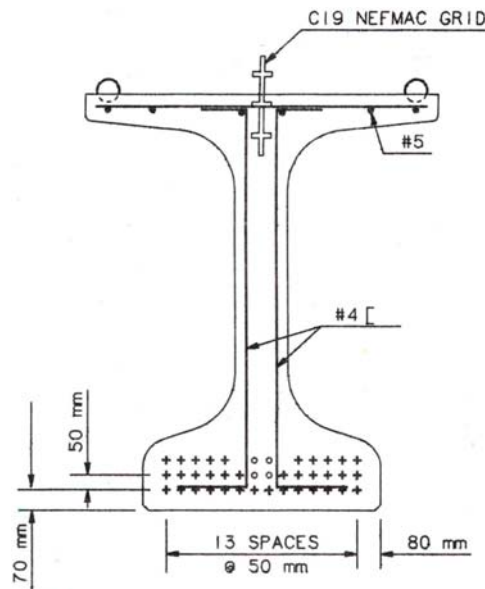
Several grid layouts and sizes were used to provide top and bottom reinforcement in the deck. All main reinforcing grids had bars spaced at 4 in. transversely, and bars at 6 or 12 in. in the longitudinal direction of the bridge. The area of each bar in main grids was  $0.248 \text{ in}^2$ , resulting in a total reinforcing area of  $0.744 \text{ in}^2/\text{ft}$  of deck in the transverse direction. For continuity of reinforcement between grids, NEFMAC strips were spliced over adjacent grids in the transverse direction of the deck (Figure 4.18). Full-scale tests were conducted at the University of New Hampshire to determine the strength of this splice detail. The minimum concrete cover over the FRP grids was 2 in.



**Figure 4.18 – Splice detail between adjacent NEFMAC reinforcing grids** (Photograph courtesy of David Scott, NH-DOT)

The NEBT girders and deck were designed to act compositely. To achieve composite action, the top flange of girders was roughened during fabrication leaving  $\frac{1}{4}$ -in. deep longitudinal grooves. In addition, shear studs cut from the FRP composite grids

were placed on the top flange of the NEBT girders during casting to extend 5 in. into the concrete deck (Figure 4.19). These studs were placed every 24 in. along the entire span of the girders.



**Figure 4.19 – Cross-section of NEBT1400 prestressed concrete girder used in the Rollins Road Bridge** (Drawing courtesy of David Scott, NH-DOT)

Ease of installation of the grid reinforcement was a major advantage of the project. The bridge deck is periodically monitored and continues to be in excellent condition. Higher cost of the composite materials was considered to be the only drawback of the use of FRP materials for this project. It is expected that the improved service-life performance of the bridge deck will help offset these higher initial material costs. The bridge construction was partially funded through the FHWA Innovative Bridge Research and Construction (IBRC) program. Total material cost of the reinforcing grids was \$200,000. The estimated cost of conventional epoxy-coated steel reinforcement for this project was \$30,000. Although there is a large difference in initial costs between conventional and composite material reinforcement, it is anticipated that the better long-term performance of the bridge deck will translate into lower maintenance costs over the service-life of the bridge. The condition of the Rollins Road Bridge before and after replacement is shown in Figure 4.20.



(a) Before construction



(b) After construction

**Figure 4.20 – Photos of the Rollins Road Bridge** (Photographs courtesy of David Scott, NH-DOT)

## 4.6 Applications in Rhode Island

### 4.6.1 Rehabilitation of Corrosion-Damaged Bridge Pier Cap

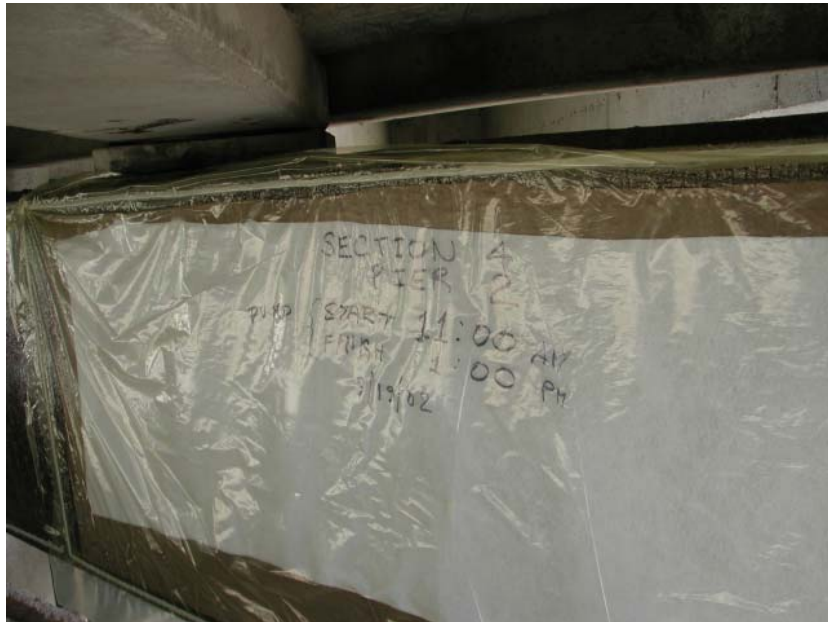
The Rhode Island Department of Transportation (RI-DOT) used FRP composites to rehabilitate pier caps in a bridge carrying traffic on US Route 1 in Silver Spring Cove. The bridge superstructure consists of prestressed concrete girders with a cast-in-place concrete deck. The prestressed concrete beams supporting the cast in place slab are in excellent condition. The pier caps supporting the prestressed girders, however, exhibited significant deterioration due to chloride-laden water that leaked through expansion joints in the bridge and the proximity of the structure to salt water (Figure 4.21).

The two northern pier caps in the bridge were protected on the top and sides with a glass fiber-reinforced composite fabric, leaving the bottom of the pier caps exposed. Prior to application of the FRP composite, spalled and deteriorated areas of concrete were patched. The 3-sided FRP jackets consisted of a glass fiber-reinforced composite in an epoxy matrix (Sikadur Hex 300) that is intended to provide an impervious barrier on the pier caps. Fiber impregnation was achieved with a low-viscosity resin applied using vacuum infusion process (Figure 4.22). This process was intended to provide complete adhesion between the fiber fabric and the uneven concrete surface of pier caps and elimination of air entrapment during the application process. During the application of the system it was observed that the vacuum-assisted impregnation process was not effectively drawing the resin into the fabric or completely eliminating air bubbles, so it was decided to use paint rollers to ensure full adhesion and saturation of the fiber fabric (Figure 4.23). Drip edges were formed so that the contaminated water would not wet the bottom part of the cap or the piers. The bridge repair is being monitored on a quarterly basis during three years by visual inspection and chloride content measurements before and after the winter season. Funding for this project was secured through FHWA's

Innovative Bridge Research and Construction Program. A picture showing one pier cap after completion of fabric application is shown in Figure 4.24.



**Figure 4.21 – Initial condition of pier cap** (Photograph courtesy of Colin Franco, RI-DOT)



**Figure 4.22 – Installation of glass fabric and plastic bag for vacuum-assisted resin infusion** (Photograph courtesy of Colin Franco, RI-DOT)



**Figure 4.23 – Removal of air bubbles between bag and glass fiber fabric** (Photograph courtesy of Colin Franco, RI-DOT)



**Figure 4.24 – Finished condition of encapsulated pier cap** (Photograph courtesy of Colin Franco, RI-DOT)

## **4.7 Applications in Vermont**

### **4.7.1 *Morristown Bridge***

The Morristown Bridge replaces a bridge located in the Town of Morristown, Vermont on Route 100 (VT-100) over the Ryder Brook. VT-100 is a principal arterial highway on the State Highway System and has a daily vehicular traffic of approximately

7,000 vehicles. In this project, the Vermont Agency of Transportation (VAOT) opted to use glass fiber-reinforced polymer reinforcing bars for construction of the reinforced concrete deck of the replacement bridge to eliminate problems associated with corrosion of steel reinforcement.

The existing bridge consisted of a 3-span T-beam concrete superstructure built in 1929 with a total length of 120 ft. The deck width was 21 ft. measured from rail to rail. Over the years, the T-beams had severely deteriorated due to corrosion rendering the existing bridge structurally deficient. Because the existing bridge was also functionally obsolete, a decision was made to replace the bridge.

The new bridge consists of an integral abutment bridge with a total span to centerlines of abutment bearings of 144 ft (147 ft. to back of abutments). The deck width of the replacement bridge is 34 ft. wide between railings. It accommodates two-12 ft. travel lanes and 5 ft. shoulders on each side of the roadway. The total construction cost of the project (1000 ft., including approach roadway) is \$1.4 million. Construction began in the Fall of 2001 and finished in Fall of 2002. The Contractor was Blow & Cote from Morristown, VT.

Several innovative features were included in the replacement bridge. The bridge was designed and constructed using integral abutments to prevent water seepage through expansion joints. To avoid corrosion, all reinforcement (top and bottom mats) for the 9-in. thick deck consisted of glass fiber-reinforced polymer (GFRP) bars instead of epoxy-coated reinforcement commonly used in this type of project. The bridge deck was instrumented during construction using fiber optic strain gages on reinforcing bars and temperature sensors inside the concrete deck. Transverse and longitudinal GFRP reinforcing bars consisted #6 bars placed at 4 and 6 in., respectively. Top and bottom concrete covers were 2.5 in. and 1.5 in., respectively. Handling of GFRP reinforcement was reportedly easier than handling conventional steel reinforcing bars. GFRP bars weigh only 0.4 lb/ft compared with a weight of 1.5 lb/ft of #6 steel reinforcing bars. The GFRP bars were fabricated by Pultrall of Thetford Mines, Quebec, Canada. The FHWA provided \$260,000 from the IBRC Program as partial support for construction of this project.

Cost was one of the main disadvantages of using GFRP reinforcement in this project. The total cost for the GFRP reinforcement was \$84,000, whereas steel reinforcement in a similar bridge would typically cost \$31,000. The GFRP bars cost \$1.43 per foot at the time of construction. Because of the low modulus of elasticity of GFRP bars (5,800,000 psi) compared with steel modulus (29,000,000 psi), crack widths are larger at a given service stress compared with steel reinforcing bars. It could be argued, however, that the non-corrosive property of GFRP bars mitigates any concern about large crack widths in concrete decks. For this project, allowable crack width limits specified for steel-reinforced decks were used as design criterion.

Bends in the GFRP have to be fabricated before bars have cured. Sharp bends cannot be made in the field because of material brittleness. For this reason, barriers were reinforced using conventional epoxy-coated reinforcement in this bridge (Figure 4.25).

Long bars, however, can be bent slightly and formed easily into a mat. GFRP bars in the bridge deck were lap-spliced for continuity as shown in Figure 4.26. A view of the completed Morristown Bridge is shown in Figure 4.27. Construction of this bridge started in May 2002 and it opened to traffic in July 2002 (Benmokrane et al. 2004). Remote monitoring of strains in GFRP bars and temperature of the deck is conducted by the University of Sherbrooke, Quebec, Canada.



**Figure 4.25 – View of deck and barrier reinforcement during deck casting**  
(Photograph courtesy of Thomas Lackey, VAOT)



**Figure 4.26 – GFRP reinforcement lap splice detail** (Photograph courtesy of Thomas Lackey, VAOT)



**Figure 4.27 – View of Morrystown Bridge after construction completion** (Photograph courtesy of Thomas Lackey, VAOT)

## 5. Conclusions

ACMs have been used primarily in transportation infrastructure as demonstration projects to date. The technology has evolved sufficiently to use these materials in mainstream applications. As discussed in this report, however, several obstacles that both producers and engineers have encountered when trying to implement these products in a new project have hindered their widespread use in the transportation infrastructure market. The most prevalent obstacles encountered by both groups were discussed in detail in Section 3.3 of this report, and include:

- Cost
- Issues with design codes
- Limited knowledge and experience with these materials
- Concerns about environmental effects and long-term behavior

Applications of ACMs in New England transportation infrastructure projects were described in Chapter 4. The large variety in the type of projects encountered highlights the diverse possibilities where these products can be applied. These materials have mostly been used in bridge applications to date, where the lack of design codes or standards significantly impacts the ability of design engineers to specify these products. It has been suggested that other applications, where life safety of the users is not affected as it is for bridge applications, would perhaps be areas where ACMs could be used more widely.

The comments received from questionnaires, project meetings, and personal communications have helped identify concerns from individuals in different groups that integrate the network of ACM usage in transportation infrastructure. This feedback was used to develop a series of suggested steps that could be taken to promote usage of ACMs in the transportation infrastructure, as discussed in the following section.

### 5.1 Suggested Steps to Promote Use of Advanced Composite Materials in Transportation Infrastructure in New England

*Increase database of projects with supplemental funding from IBRC* – ACMs are not used widely because of their high initial cost compared with traditional materials used in civil engineering. Supplemental funding from the federal government in innovative applications could assist in offsetting that cost difference and would allow states to develop innovative applications in collaboration with research institutions and fabricators of ACM products in future projects. This collaborative effort has resulted in very positive experiences in past projects as showcased in several applications in Maine.

*Continue to monitor performance of existing applications* – this activity will help develop confidence on the long-term performance of these products and will provide

much needed data on maintenance costs compared with other materials used currently in the transportation infrastructure.

*Familiarize engineers with materials through seminars/workshops* – in recent years, a number of design documents have been published that will begin to bridge the gap between research and practical applications of ACMs. Engineers could become familiarized with these documents through attendance to seminars/workshops that focus on the practical implementation of these materials in design applications. Transportation agencies can engage individuals at educational institutions to develop and conduct these seminars on-site. In the seminars engineers would also receive information that would assist them in becoming familiarized with composite materials technology so that they can at least speak the same language as people in the composites industry.

*Establish close communication between engineers and producers* – it was apparent in several stages throughout the project that many obstacles to implement ACMs in the transportation infrastructure could be eliminated or reduced by establishing communication channels between ACM product manufacturers and transportation agency engineers. ACM fabricators are not typically familiar with design codes in civil engineering and conversely engineers in transportation agencies are not familiar with all the details of polymer technology. Engineers should be able to communicate the expected performance that is needed of a product to the fabricators, and fabricators should be able to guarantee quantitatively that the performance is achieved from their design (e.g. if the product needs to be impact resistant then specify the amount of energy that should be absorbed and communicate that to the fabricator).

*Identify potential applications where ACMs would be beneficial* – a critical first step for immediate implementation of ACM products in future transportation infrastructure applications is to identify applications where these materials are cost-competitive with traditional civil engineering materials. From conversations with ACM fabricators a first possibility would be applications where piping (or other closed sections) are needed because the fabrication method for these products is very inexpensive. Another application where ACMs might be used cost-competitively is for signs or other flat surfaces.

As the paragraphs above imply, unilateral efforts by one group are not sufficient for an effective expansion on the use of ACMs. It is therefore recommended that partnerships between ACM manufacturers, research institutions, and transportation agencies be established for successful implementation of these materials in the transportation infrastructure. Each group would play a significant role in product implementation as described below:

*Role of ACM manufacturer* – provide experience with adequate manufacturing techniques, appropriate resins and fibers, fiber architecture; provide information on best materials for expected physical and environmental conditions; give input on possible ways that cost could be reduced;

*Role of DOT engineer* – development of design details, identification of performance requirements, general project oversight, serve as engineer of record, ensure constructability of project using FRP product, work with fabricators to develop inspection protocols.

*Role of research institution* – provide quality control services until transportation agencies have necessary testing equipment to conduct ASTM composite material tests, evaluate performance of products through physical testing, develop analytical tools that can be used in practice for design of ACM products, provide field monitoring services to independently evaluate long-term performance of products. If the application is innovative, physical testing of components fabricated using the same procedures as those used for the actual project is recommended. A large variety of research laboratories (federally funded, universities, private institutions) are available within New England that could provide independent verification of a particular product so that it satisfies the desired performance.

ACMs have become a viable alternative to traditional materials in specific applications within the transportation infrastructure market. Bridge decks fabricated using innovative designs with composite materials, externally bonded composites used for retrofit applications, and reinforcing products for concrete construction (internal and external) are some examples of applications where composites will probably continue to be used effectively. An extension to composites being used in other applications depends on establishment of open communication lines between engineers and fabricators so that ideal applications can be identified and new cost-competitive products can be developed. This research project attempted to provide an initial step along these lines with the hope of being able to spark enough interest to develop future collaborations among engineers, fabricators, and researchers involved in this market.

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## Appendix A: Advanced Composite Material Fabricators in New England

**Table A.1 – Fabricators in Connecticut**

<b>Company and Location</b>	<b>Descriptions and Products Offered</b>	<b>Contact Numbers</b>	<b>Survey Response?</b>
Current Inc. 30 Tyler St. East Haven CT 06512	Composite Mfg. For infrastructure, mass transit, and industrial app. Compression, vacuum, and autoclave molding. Phenolic, epoxy, silicone, and melamine are some of their resin systems.	Tel: 887 436 6542 Fax: 203 467 8435	Yes
Advanced Materials Inc. 11 Colton Rd. East Lyme, CT 06333	Custom molding for utility industry, manhole covers and pole top extensions.	Tel: 860 691 8350 Fax: 860 691 8355	Yes
Chromalloy Connecticut 22-T Barnes Industrial Rd., P.O. Box 748 Wallingford CT 06492 0748	Compression Molded Composites, Jet Engine Components.	Tel: 207 594 8821 Fax: 207 594 1049	No
Saint-Gobain Performance Plastic Rubber 407 East St. New Haven CT 06511	Mfr. Of Engineered Products Made Primarily From Specialty Formulated Polymer Materials. Gasket Tapes. Specialty Film Tapes, Thermally Conductive Elastomers, Slit Rolls, Die Cut Parts	Tel: 800 777 2647 Fax: 203 787 1725	No
E.J. Davis Company 10 Dodge Ave Wharton Brook Ind. Center P.O. Box 326 North Haven CT 06473	Thermal and acoustical insulation materials. Custom parts (smaller parts)	Tel: 203 239 5391 Fax: 203 234 7724	No

**Table A.2 - Fabricators in Maine**

<b>Company and Location</b>	<b>Descriptions and Products Offered</b>	<b>Contact Numbers</b>	<b>Survey Response?</b>
Kenway Corp. 681 Riverside Dr. Augusta ME 04330	Fiberglass reinforced plastic piping, tanks, hoods, fittings & ducts FRP trench liner Optional FRP grating as well Manhole covers, handrails Mold manufacturing capabilities, custom molded products	Tel: 207 622 6229 Fax: 207 622 6611	Yes
Maine Composites Inc. 150 Main Street, Ste #1 Richmond, ME 04357	Interested in pursuing carbon epoxy rods and cables.	Tel: 207 737 8784 Fax: 207 737 8471	Yes
Custom Composite Technologies 15 Wing Farm Parkway Bath, ME 04530	Use hand lay up, vacuum bagging, RTM and infused laminates. Utilizing many materials for custom molds.	Tel: 207 442 7007 Fax: 207 442 7050	Yes
North End Composites 28-T Gordon Dr., P.O. Box 548 Rockland ME 04841	Leader in all of the latest composite technologies and is today one of the mostly highly regarded tooling and lamination yards in the industry.	Tel: 207 594 8821 Fax: 207 594 1049	Yes
Harbor Technologies, Inc. 228 Old Portland Rd. Brunswick, ME 04011	FRP docks, pilings, sheetpile.	Tel: 207 725 4878 Fax: 207 725 4878	Yes
Bear Creek Canoe Inc. Rte. 11, R.R. 1, Box 163B Limerick ME 04048	Fibreglass Canoes and related accessories manufacturer. Moldings, Sleds.	Tel: 207 793 2005 Fax: 207 793 4733	Yes

**Table A.3 – Fabricators in Massachusetts**

<b>Company and Location</b>	<b>Descriptions and Products Offered</b>	<b>Contact Numbers</b>	<b>Survey Response?</b>
New England Plastics Corp. 308 Salem St. Woburn MA 01801	Conductive Tote Boxes, Custom Molding, Tote Aalls, Valu Liner Drum, and Pail Liners. Rotational Molding	Tel: 781 933 6004 Fax: 781 933 2723	No
Accurate Plastics Inc. 33 Tech Park Dr. Falmouth MA 02536	Laminated thermoset plastics. Sheets, rods, tubes, angles and parts.	Tel: 800 222 8759 Fax: 508 457 9275	No
MicroMarine, Ltd. 7 Industrial Park Road Medway MA 02053	Recreational boating redefined 14' 8" long high density polyethylene hulls	Tel: 800 451 8746 Fax: 508 533 8070	No
Power Engineering Co. Inc. 420 Boston Tpke. Shrewsbury MA 01545	Complete Line Of Safety Grating Which Includes Grip Strut In All Materials & Bar Grating In Steel, Stainless, Aluminum & Fiberglass. Molded and Pultruded Fiberglass	Tel: 800 274 1303 Fax: 508 842 9833	No
Bay Sails Marine 2566 RTE. 6 Box 1455 Wellfleet, MA 02667	Full service boat yard and boat dealer. Custom manufacturer of distributor of marine technology.	Tel: 508 349 3840 Fax: 508 349 7982	Yes
Geonautics Manufacturing, Inc. 506-T Merrimac St., P.O. Box 230 Newburyport MA 01950	Design, Development & Production: Custom & Precision Reinforced Plastics. Molding, Lay-Up & Machining: Aerospace, Marine & Electronic Marketplace. Phenolics, Polyesters, Epoxies, Fiberglass, Silica & Kevlar	Tel: 877 462 4776 Fax: 978 462 7764	Yes
McNichols Co. 45 Power Rd Westford MA 01886	Molded Fiberglass Grating 72 % drainage	Tel: 800 237 3820 Fax: 978 692 0044	No

**Table A.3 (cont.) – Fabricators in Massachusetts**

<b>Company and Location</b>	<b>Descriptions and Products Offered</b>	<b>Contact Numbers</b>	<b>Survey Response?</b>
IKG Industries 12 Kane Industrial Dr Hudson MA 01749	CorGrate Fiberglass Grating, CorLight Fiberglass Structural	Tel: 978 568 8771	No
Coast-Line International NY, MA, GA	Serving Composite Industry with a complete line of materials since 1960	Tel: 631 226 0500 Fax: 631 226 5190	No
Fiber Innovations 24 Walpole Park South Walpole MA 02081	Triaxial Braiding, Preform Stitching, Complex Shapes Resin Transfer Molding, Custom Fabrication Discrete Molded Structures	Tel: 508 660 2622 Fax: 508 660 6662	Yes
CAD CUT Montpelier VT Marblehead MA	Cutting and Kitting Prepreg and Dry Fabric Custom Manufacturers, Packaged Ply Kits	Tel: 781 639 2900 Fax: 781 639 3565	

**Table A.4 – Fabricators in New Hampshire**

<b>Company and Location</b>	<b>Descriptions and Products Offered</b>	<b>Contact Numbers</b>	<b>Survey Response?</b>
Dumont Design & Fabrication 28-T Duklee R-T Bow NH 03304	Prefabricated fiberglass platforms, catwalks, walkways, ped bridges, handrails, gratings, structures Structural Fiberglass (GRP FRP)	Tel: 877 228 1606 Fax: 603 228 1654	No

**Table A.5 – Fabricators in Rhode Island**

<b>Company and Location</b>	<b>Descriptions and Products Offered</b>	<b>Contact Numbers</b>	<b>Survey Response?</b>
Applied Plastics Technology, Inc. 45 Broad Common Rd., P.O. Box 45 Bristol, RI 02809 2721	PTFE Molding, Processing, Machining, Fabricating. New Part Design. Computer Controlled Automatic PTFE Molding & Machining Equipment. Markets Served Include, Military, Aerospace, Automotive, Chemical Processing, Pumps & Valves, Medical, Connector, Appliance, Compressors, Food Processing, Equipment, Semi-Conductor.	Tel: 401 253 0200 Fax: 401 253 0474	No
Jade Engineered Plastics, Inc. 121 Broad Common Rd. Bristol RI 02809	Leader in the custom compression molding and fabrication of PTFE parts for some of the most rigorous applications in a wide variety of industries	Tel: 800 787 1729 Fax: 401 253 1605	No
Meikle Marine & Machine Inc. 51 Eagleville Rd. Tiverton RI 02878	Composites, Fiberglass & Metal Fabricators Wing-in-ground effect craft Working on making signs from fiberglass, to replace aluminum	Tel: 401 624 8450 Fax: 401 683 7896	No
TPI Composites, Inc. 373 Market Street Warren, RI 02885	Products for the wind energy, military vehicle, and transportation markets. Use a proprietary resin transfer technology (SCRIMP technology) to fabricate materials.	Tel: 401 247 4010 Fax: 401 247 2669	No

**Table A.6 – Fabricators in Vermont**

Vermont Composites 139 Shields Dr Bennington VT 05201	Composite parts for medical, aerospace, industrial market Medical tables to launch vehicle structures and avionic enclosures	Tel: 802 442 9964 Fax: 802 447 3642	No
Lucas Industries 201 Clinton St Springfield VT 05156	Specializing in design and fabricating intricate tools, parts, models, molds and patterns. Lucas uses almost every metallic/nonmetallic material available. These materials include wood, epoxy, urethanes, foams and rubbers.	Tel: 802 885 4644 Fax: 802 885 4995	Yes
Newport Plastics Corp. P.O. Box 988 Lyndonville VT 05851	Fiberglass Reinforced Plastics, Honeycomb Panel Work, Vacuum Bagging	Tel: 802 626 4000 Fax: 802 626 4176	Yes
CAD CUT Montpelier VT Marblehead MA	Cutting and Kitting Prepreg and Dry Fabric Custom Manufacturers, Packaged Ply Kits	Tel: 781 639 2900 Fax: 781 639 3565	No

## Appendix B: Questionnaires

### B.1 Survey Questions Sent to Advanced Composite Material Manufacturers

#### *General Information*

1. How would you classify your knowledge on FRP materials (please check box as appropriate)?

- ☐ High (material behavior, composition of materials, manufacturing processes, suitable applications, limitations of materials).
- ☐ Very familiar (have some knowledge on basic properties, some manufacturing processes).
- ☐ Somewhat familiar (have heard of applications, are not familiar with composition, do not know limitations).
- ☐ Have no previous knowledge or experience (first time having heard of them)

#### *FRP Materials in Transportation Applications*

1. Does your organization currently fabricate fiber reinforced polymer products?

☐

YES

☐

NO

2. What products does your company currently manufacture?

3. What manufacturing processes does your company utilize to make those products?

4. Some of the FRP applications being considered include bridge girders and decking, reinforcement, overhead sign structures, signs, guardrail, piping, grating, manholes, posts, pilings and retaining walls. Does your company have the equipment or resources to manufacture the possible FRP applications described above? If yes please list which applications. Please list any other products that may be adequate for transportation infrastructure usage.

☐

YES

☐

NO

5. Has your company ever produced FRP products for a transportation application? If yes please describe the project and people that could provide additional information.

☐

YES

☐

NO

6. What advantages or impediments/concerns do you think may arise with the use of FRP materials in New England's highway systems, in comparison with traditional materials (steel, wood, concrete). Please indicate if these impediments have prevented you or anyone in your organization from expanding into transportation-related projects.

<b><i>Advantages of FRP Applications</i></b>	<b><i>Disadvantages of FRP Applications</i></b>

7. Would your company like to participate in the exchange of information to promote the usage of FRP products in the local transportation network?

☐

YES

☐

NO

8. Considering the market potential, would your organization be willing to work with DOT's of New England to produce FRP application for infrastructure in the future? Participation may include meetings interacting with engineers to facilitate usage of your products in highway projects.

☐

YES

☐

NO

9. Please list any other industrial organizations/suppliers that you feel would be a helpful contact for this study.

<b>Company</b>	<b>Contact Information</b>	<b>Worked with? Y/N</b>

## **B.2 Survey Questions Sent to Members of Transportation Agencies**

### ***General Information***

1. How would you classify your knowledge on FRP materials (please check box as appropriate)?

- ☐ High (material behavior, composition of materials, manufacturing processes, suitable applications, limitations of materials).
- ☐ Very familiar (have some knowledge on basic properties, some manufacturing processes).
- ☐ Somewhat familiar (have heard of applications, are not familiar with composition, do not know limitations).
- ☐ Have no previous knowledge or experience (first time having heard of them)

### ***FRP Materials in Transportation Applications***

1. Has your organization used products fabricated using FRP materials or has applied FRP materials in transportation applications?

☐

YES

☐

NO

2. If YES, please list the applications in the following table (please use additional pages if needed); if NO go to question (3):

<b>Application:</b>
<b>FRP material selected (fiber and resin type; fabrication procedure):</b>
<b>Other Materials Considered:</b>
<b>Reason for Using FRP Materials:</b>
<b>Obstacles encountered in the implementation of the FRP products:</b>
<b>Please describe the performance of the FRP product(s) so far. If unsatisfactory, describe reason.</b>

3. Has your organization ever considered the use of FRP products as an alternative to products fabricated using traditional materials (concrete, steel, wood, plastics) in transportation applications, but was ultimately decided not to implement them?

☐

YES

☐

NO

4. If YES, please list the applications in the following table (please use extra pages if needed); if NO go to question (5)

<b>Product or application:</b>
<i>FRP material selected (fiber and resin type; fabrication procedure):</i>
<i>Describe product it would be replacing (if any):</i>
<i>Reason for considering FRP materials:</i>
<i>Reason for not implementing the FRP solution:</i>

5. Please list any current or future project(s) where your organization is considering the use of FRP materials or products in the following table (use extra pages if necessary). If no application is currently being considered please answer NONE below.

<b>Project and product being considered:</b>
<i>Status of project (design, construction, etc.):</i>
<i>FRP material selected (fiber and resin type; fabrication procedure):</i>
<i>Reason for considering FRP products:</i>
<i>Obstacles encountered for implementation (if any):</i>

6. List any areas in the design of transportation systems where you think that FRP materials could provide advantages over, or a reasonable replacement, to current materials.
  
7. List any concerns that you have regarding the use of FRP materials in transportation systems.
  
8. Please list research areas on the use of FRP products currently being conducted or sponsored by your organization.
  
9. List any suppliers/manufacturers of FRP materials that you are aware of (please indicate those that you have worked with in the past).

Company	Contact Information	Worked with? Y/N