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CONSTRUCTABILITY, MAINTAINABILITY, AND OPERABILITY OF FIBER REINFORCED POLYMER (FRP) BRIDGE DECK PANELS

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16. Abstract

Recent advances in composite materials for civil engineering have created interesting possibilities for replacing conventional structural forms with components made out of fiber reinforced composite materials. Composite materials offer several advantages over conventional materials such as a superior strength/weight ratio, a better stiffness/weight ratio, a high degree of chemical inertness, and flexible custom design characteristics. Some of the potential down-stream benefits include lower life-cycle costs, lighter members, high corrosion and fatigue resistance, and higher live load capacity (Seible and Karbhari 1996).

Composite materials are clearly having a major impact on how facilities are designed, constructed, and maintained. In order to enhance the application of fiber-reinforced composites in infrastructure renewal, it will be important to understand the constructability, maintainability and operability issues related to the use of Fiber Reinforced Polymer (FRP) structural components. The main objective of this project is to evaluate the constructability, maintainability and operability issues related to FRP bridge decks as compared to conventional deck construction. In order to achieve the objective, this research identified (i) the state of the art (research & development) and also state of practice of fabrication and use of composite bridge decks both in new bridges and in rehabilitation projects, (ii) issues related to constructability, maintainability, and operability of FRP bridge decks, fabrication issues, construction methods, quality, safety, man-hour requirements, cost and productivity issues, as well the skill level required, and (iii) determined the productivity, man-hour requirement, and system bottlenecks that were important for understanding the construction process and to develop construction guidelines for FRP bridge deck construction. The data required for this project were collected through questionnaire survey, interviews, and case studies.

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CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Recent advances in composite materials for civil engineering have created interesting possibilities for replacing conventional structural forms with components made out of fiber reinforced composite materials. Composite materials offer several advantages over conventional materials such as a superior strength/weight ratio, a better stiffness/weight ratio, a high degree of chemical inertness, and flexible custom design characteristics. In a recent article in the Engineering News Record, James Roberts of the California Department of Transportation was quoted as follows: "Quick-setting concrete, nighttime work, composite materials for both decks and whole structures, and large incentives for contractors will be tools for faster construction…" (ENR, June 11, 2001).

Some of the potential down-stream benefits include lower life-cycle costs, lighter members, high corrosion and fatigue resistance, and higher live load capacity (Seible and Karbhari 1996). The mass production capabilities of composite members offer possibilities for schedule compression, productivity and quality improvement, savings in labor and material costs, enhanced durability, and performance reliability (Mirmiran 1995, Kelly 1989, Gall 1986). Weight reduction and modular properties of composite members also lend to improved transportability, ease of installation, and less need for heavy equipment. Although initial investment for the production of composite members may be higher than conventional materials, it is likely to fall as the demand for composites increases (Goldstein 1996, Partridge 1989).

Composite materials are clearly having a major impact on how facilities are designed, constructed, and maintained. In order to enhance the application of fiber-reinforced composites in infrastructure renewal, it is important to understand the constructability, maintainability and operability issues related to the use of Fiber Reinforced Polymer (FRP) structural components. This research evaluates the constructability, maintainability and operability issues related to FRP bridge decks as compared to conventional deck construction.

1.2 Objective and Scope of Research

It is the objective of this research to develop construction guideline for FRP bridge deck. Some of the specific objectives of the study include:

- To identify state of the art (research and development) and also state of practice of fabrication and use of composite bridge decks both in new bridges and in rehabilitation projects.
- To identify issues related to constructability, maintainability, and operability of FRP bridge decks, fabrication issues, construction methods, quality, safety, man-hour requirements, cost and productivity issues, as well the skill level required.

- To determine the productivity, man-hour requirement, and system bottlenecks that were important for understanding the construction process and to develop construction guidelines for FRP bridge deck construction.
- Research report that documents the research process and the results obtained.

To achieve these objectives, the data related to the proposed process modeling and simulation were collected through a questionnaire survey, interviews, and case studies.

1.3 Research Framework and Methodology

1.3.1 Task-1: Literature Review

An extensive literature review was conducted to identify state of the art (research and development) and state of practice of fabrication and use of composite bridge decks both in new bridges and in rehab projects. The literature review also assists in identifying the constructability issues as well as the variables that differentiate between conventional deck construction and that using composite and/or FRP bridge deck panels. Additionally, a questionnaire survey was conducted. The questionnaire addressed issues such as constructability, maintainability, and operability of FRP bridge decks, fabrication issues, construction methods, man-hour requirements, cost and productivity issues, as well the skill level required. The questionnaire was sent to all the State DOTs.

1.3.2 Task-2: Preliminary Data Collection

The prime data requirements for achieving the stated objectives included:

- Data on standard techniques and materials used for conventional as well as FRP deck construction.
- Data on man-hour requirement, cost, duration, productivity and efficiency, as well as any limitations and barriers to the construction of FRP decks as compared to conventional deck construction.
- Identification of issues that would impact the design, construction, quality, cost, safety as well as constructability, operability, and maintainability of FRP decks when compared to conventional deck construction.

The data required for this research were collected through questionnaires, case studies, personnel interviews, and existing literature. Additionally, information was solicited from various research institutions, fabricators of FRP decks, as well as state and private agencies that have developed and utilized composite material applications for bridge deck application. Three questionnaire studies were conducted during the course of the research (i) questionnaire survey–I was sent to all DOTs as well as to State and county engineers of the case study candidate projects, (ii) questionnaire-II was sent to the two manufacturers, Hardcore Composites, and Martin Marietta, to gather specific data after conducting personal interviews with their representatives, (iii) questionnaire-III was used to collect project specific information with respect to productivity, process, and resource requirements in order to develop process simulation models.

1.3.3 Task-3: Identification of Candidate Projects

Seven candidate projects for FRP bride deck construction were identified for on-site data collection and study. Field studies allowed the observation and analyses of the installation of advanced modular deck systems to evaluate benefits due to speed and ease of installation. The candidate projects were located in Ohio.

To perform a comparative analysis of conventional versus FRP bridge deck construction, additional data were collected from conventional bridge deck projects that utilized precast concrete deck panels.

1.3.4 Task-4: Detailed Data Collection, Analysis, and Process Modeling

Process modeling and simulation were used to determine the productivity, man-hour requirement, and system bottlenecks that were important for understanding the construction process and to develop standard construction guidelines for FRP bridge deck construction. Initial process modeling was done based on the data collected through available literature and questionnaire survey. Additional data required for comparing the conventional versus FRP deck construction were collected through case studies and personnel interviews and included cost, skilled/unskilled man-hour requirement, limitations, and barriers such as technological barrier or skill requirement. Technical barriers typically included the lack of professional experience in the use of composite materials and manufacturing challenges associated with innovative design. On the other hand, economic barriers usually included the high initial cost of production and lack of data on life cycle cost/benefits of new materials.

1.3.5 Task-5: Development of Construction guideline

In order to develop construction guidelines for FRP bridge deck construction, different types of modular deck systems were evaluated to understand the issues that would impact design, construction, quality, cost, safety, as well as constructability, operability, and maintainability of FRP bridge decks. The data required for this analysis were collected through available literature, questionnaire survey, and field data collection. Based on the results of the previous tasks, standard construction guidelines were developed for INDOT.

1.3.6 Task-6: Develop Final Report

INDOT personnel were kept informed of the outcome of this study and their suggestions and comments were actively solicited. The work performed in this study was documented in a draft report and submitted to INDOT for review and comments four months prior to the scheduled completion date of the project. The comments provided by INDOT were incorporated and a final report was delivered to INDOT by the completion date of the project.

1.4 Benefits of Research

The proposed research has a strong potential to make definite impact on the application of composites in bridge deck construction. Recent advances in the use of composite materials have started to show real benefits for the construction industry, but there are significant barriers to widespread use in the industry. This research has focused on identifying the constructability, operability, and maintainability issues with respect to FRP bridge deck construction. Additionally, this research has developed construction guidelines for the use of FRP bridge deck construction that incorporates issues that impact construction, quality, cost, safety, as well as constructability, operability, and maintainability of FRP bridge decks.

1.5 Organization of the report

This report is composed of six chapters. Chapter 1 provides a general overview of the current practices and obstacles on the application of FRP bridge deck panels. This section also highlights the objectives and scope of this research, and provides a brief overview of methodologies used in realizing the stated objectives. An extensive literature review introduced in Chapter 2 includes: (i) FRP composite materials for bridge applications, (ii) challenges and technical issues in their application, (iii) advantages and disadvantages of FRP composite materials, (iv) manufacturing processes for composites, (v) composite manufacturers, (vi) previous analytical and experimental works on FRP bridge deck panels, (vii) construction procedure for FRP bridge deck panels as recommended by manufacturers, and (viii) challenges and technical issues in their application.

Preliminary data collection through questionnaire survey-I that was sent to all State DOTs and the data analyses are discussed in Chapter 3. Additional preliminary data collection and analyses through case studies, interviews, and the questionnaire survey-I that was sent to county engineers are discussed in Chapter 4.

Chapter 5 illustrates process modeling and simulation study of the construction process for the conventional versus FRP bridge deck panels. Chapter 6 describes the standard construction guidelines developed for the FRP bridge deck panels. Finally, the summary of research, main finding, and recommendation for future research are also introduced in Chapter 6.

CHAPTER 2: Literature Review

2.1 FRP composite materials for bridge applications

Developed 30 years ago for the aerospace industry, fiber-reinforced polymer (FRP) materials have been used in various applications. In particular, recent advances in composite materials for civil engineering have created interesting possibilities for replacing conventional structural forms with components made out of fiber reinforced composite materials. More and more civil engineers are beginning to gain confidence and experience in applying composite materials to civil structures. There are more than 80 bridge projects worldwide using FRP composites materials and about 30 projects in the U.S., 26 of which were built within the last 4 years (SPI 1998).

Fiber-Reinforced Polymer (FRP) composites is defined as a polymer matrix that is reinforced with a fiber or other reinforcing material with a sufficient aspect ratio to provide a reinforcing function in one or more directions. Composite materials are clearly having a major impact on how facilities are designed, constructed, and maintained. In order to enhance the application of fiber-reinforced composites in infrastructure, it will be important to understand the constructability, maintainability and operability issues related to the use of FRP structural components. These new materials are applicable to both construction of new structures and maintenance and rehabilitation of existing bridges. In particular, bridge decks have received the greatest amount of attention in the past few years, due to their inherent advantages in strength and stiffness as compared to traditional steel reinforced concrete decks. Reducing the weight of replacement decks in rehabilitation projects also presents the opportunity for rapid placement and reduction in dead load, thus raising the live load rating of the structure (Alampalli et al. 1999).

2.2 Advantage and Disadvantage of FRP Composite Materials

Composite materials of FRP bridge decks are typically made with vinyl ester or polyester resin reinforced with E-glass fiber. They are engineered and fabricated in a controlled factory then assembled and installed at a bridge site where a wearing surface is added. These characteristics of composite materials offer several advantages over conventional materials providing large incentives for contractors as a tool for faster construction. Other significant advantages include a superior strength/weight ratio, a better stiffness/weight ratio, a high degree of chemical inertness, and flexible custom design characteristics. However, there are still some unfavorable characteristics of FRP composites materials such as high initial cost, design restriction, and limited experiences that prevent their wide application in civil infrastructure.

2.2.1 Advantage

Composite materials have many advantages over conventional materials such as lower life-cycle costs, lighter members, high corrosion and fatigue resistance, and higher live load capacity (Seible and Karbhari 1996). The mass production capabilities of composite materials also offer possibilities for schedule compression, productivity and quality improvement, savings in labor and material costs, enhanced durability, and performance reliability (Mirmiran 1995, Kelly 1989, Gall 1986). Weight reduction and modular properties of composite materials also provides improved transportability, ease of installation, and less need for heavy equipment. Although initial investment for the production of composite materials may be higher than conventional materials, it is likely to fall if the demand for composites increases (Goldstein 1996, Partridge 1989).

Table 2-1 Typical Advantages of FRP Bridge Deck (O'Connor 2003)

No.	Advantages
1	Light weight.
2	Resistance to de-icing salts and other chemicals
3	Fast installation
4	Good durability
5	Lower user costs, less expense for maintenance and protection of traffic, and better public relations due to reduced traffic delay
6	Long service life.
7	Fatigue resistance
8	Good quality due to fabrication in a controlled environment
9	Ease of installation.
10	Cost savings

As seen in Table 2-1, its lightweight material and ease of construction provide significant labor and traffic control cost savings to offset a higher initial cost of FRP application. An FRP deck could reduce the weight of conventional construction by 70 to 80 percent. In addition, the modular panel construction of bridge deck enables fast project delivery. A bridge built of composite materials can be constructed and put in service in a relatively short duration. This technology has demonstrated that a bridge structure can be replaced and put into service in a matter of hours rather than days or months compared to conventional materials (Tang and Podolny 1998).

2.2.2 Disadvantage

In spite of many advantages over the conventional materials, FRP bridge deck has many drawbacks to resolve such as high initial cost, restricted design, limited experiences, and so on. Its higher initial cost is the most concern for application of FRP bridge deck. Even though the added expense is offset by other savings such as maintenance and protection of traffic, the unit cost of FRP materials is often more expensive than conventional materials. The other concern is related to the FRP material properties due to inexperience within the construction industry. There are few FRP bridges that have been in service for any substantial length of time. This resulted in lack of long term performance data, lack of design standards as addressed in Table 2-2.

Table 2-2 Typical Disadvantages of FRP Bridge Deck (O'Connor 2003)

No.	Advantages
1	High initial cost
2	Deflection driven design due to FRP's low modulus of elasticity
3	No standard manufacturing process.
4	Sensitive response to thermal change than concrete and steel
5	Some failure of the wearing surface (i.e. cracking, debonding)
7	The resultant tendency to creep over time
8	Limited FRP experience within the construction industry
9	Lack of long term performance data
10	Lack of design standards

As seen in Table 2-1, higher initial cost compared to a conventional concrete deck is the most significant problem to resolve. In addition, FRP's low modulus of elasticity leads to a deflection driven design which does not allow a designer to fully capitalize on the FRP's strength. Also, currently available designs are proprietary so that there is no standard manufacturing process. In particular, response to thermal change is slightly different than for concrete and steel so that it requires special consideration when an FRP deck is used on a concrete or steel superstructure.

FRP material properties like strength and stiffness naturally degrade over time. The resultant tendency to creep is another disadvantage. Some past projects have experienced a failure of the wearing surface (i.e. cracking and/or debonding). Appropriate strength reduction factors need to be used to insure adequate stiffness over the entire service life of the structure.

2.3 Composites Manufacturing Processes

In this section, typical manufacturing processes used by FRP composite bridge deck manufacturers are addressed. There are many different manufacturing processes available to the composites manufacturer. Each fabrication process has its own characteristics that define the type of products that can be produced. Is spite of this, generic manufacturing processes can be divided into two types: open molding and closed molding.

2.4.1 Open Molding

Open molding is a common process for making fiberglass composite materials employed in the industry. Once the product has cured, then it is removed from the mold and the mold is used for the next product. Therefore, companies can inexpensively make a wide variety of products. The raw materials are applied by hand or by spray into the open mold. Usually, the mold is left open while the materials react and harden, or "cure". It is typically used for making boat hulls and decks, RV components, truck cabs and fenders, spas, bathtubs, shower stalls and other relatively large, non-complex shapes. The open molding involves either spray-up or hand lay-up. Both methods are often used together to reduce labor.

(1) Hand Lay-up (Wet Lay-up) Process

Hand lay-up is an open molding method for making various composites products such as boats, bath-ware, housing, auto components, and many other products. Though the production volume per mold is low, it is feasible to produce substantial product quantities using multiple molds. In a particular hand lay-up process, high solubility resin is sprayed, poured, or brushed into a mold where the reinforcement is placed. Depending upon the thickness or density of the reinforcement, it may receive additional resin to improve saturation and allow better draping into the mold surface. The reinforcement is then rolled, brushed, or applied using a squeegee to remove entrapped air and to compact it against the mold surface (Busel and Lockwood 2002).

(2) Spray-up (Chopped Laminate) Process

Spry-up or chopping process is an open mold method similar to hand lay-up in its suitability. In the spray-up process, the mold is first treated with mold release. If a gel coat is used, it is typically sprayed into the mold after the mold release has been applied. The gel coat is then moved to be cured in a heated oven at about 120°F and then, the mold is ready for fabrication. In the spray-up process, catalyzed resin and glass fiber are sprayed into the mold using a chopper gun that blows the short fibers directly into a sprayed resin stream so that both materials are applied at the same time.

Finally, the laminate is compacted by hand with rollers. Wood, foam or other core material may be added, and a second spray-up layer is applied to embed the core between the laminate skins. The part is then cured, cooled and removed from the reusable mold (Composite World 2003)

(3) Filament Winding

The filament winding process is used for tubular composite parts such as composite pipe, electrical conduit, and composite tanks. Fiberglass roving strands are impregnated with a liquid thermosetting resin and wrapped onto a rotating mandrel in a specific pattern (Busel and Lockwood 2002). After the winding operation, the resin is cured or polymerized and the composite part is removed from the mandrel.

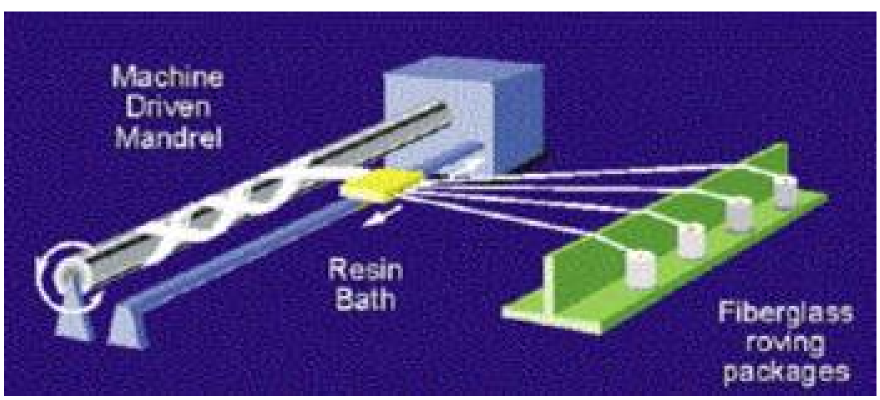

Figure 2-1 Diagram of Filament Winding Process (Busel and Lockwood 2002)

Figure 2-1 shows typical diagram of filament winding process. However, initial capital investment is relatively higher compared to other open mold processes. The primary portion of largest expense for an existing filament winder is the cost of the winding mandrel (Busel and Lockwood 2002).

2.4.2 Closed Molding

With advancements in FRP composite materials in recent years, closed molding has become a viable technology reducing emissions and optimizing the glass-resin ratio. It produces a higher quality laminate and allows both sides of the part to have a finished appearance. In the closed molding, liquid resin is not exposed to the air. However, this process is much more expensive than open molding. Closed Molding is only used where the higher product quality is needed. There are several types of closed molding processes as follows

(1) Resin Transfer Molding (RTM)

Resin Transfer Molding (RTM) is one of lowest cost manufacturing process that has received a lot of attention in recent years. As shown in Figure 2-2, the dry fiber reinforcement is arranged into a pre-form placed in a mold. The mold is closed and resin is injected into the mold under relatively low pressures until the entire cavity is filled. After the resin is cured, the finished part is removed from the mold.

RTM produces parts that do not need to be autoclaved. A part designed for a high-temperature application usually undergoes post-cure. Most RTM applications use a two-part epoxy formulation. Vacuum is sometimes used to enhance the resin flow and reduce void formation. The part is typically cured with heat (Composite World 2003).

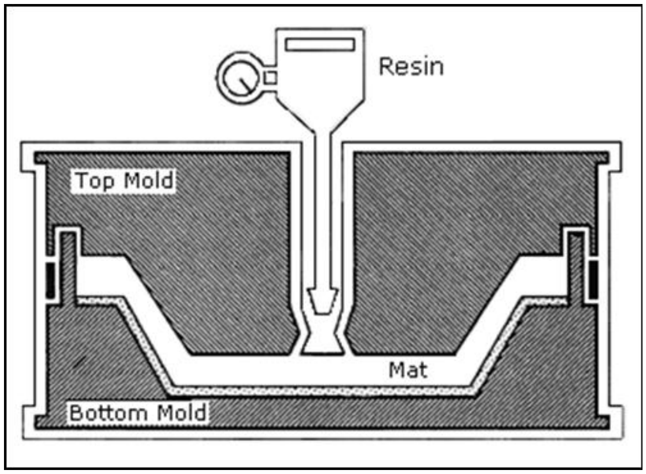

Figure 2-2 Matched Molds Used in RTM (Busel and Lockwood 2003)

The benefits of RTM are that the mold surface can produce a high quality finish and it can produce parts as much as 5~20 times faster than open molding method. In addition, complex mold shapes are possible and emissions are lower than open mold process (Busel and Lockwood 2002).

(2) Resin Infusion Molding (RIM)

Resin Infusion Molding (RIM) shares many characteristics of vacuum bag molding and resin transfer molding (RTM). Like RTM, infusion reduces styrene emissions by wetting out and curing the laminate in a closed system. With a single shot, the infusion process creates a high performance laminate eliminating potential bonding problems. This process is possible to attain fiber to resin ratios as high as 70:30 along with the virtual elimination of air entrapment and voids. This process necessitate a mold similar to that of any open molding process and a unitary vacuum.

(3) Injection Molding

Injection molding is one of the oldest processes for plastics and the most closed process. A compound is pumped into a steel mold and the melted plastic is injected into a heated mold where the part is formed. This process is often fully automated (Busel et a. 2000).

(4) Pultrusion

Pultrusion is an automated manufacturing process for the production fiber reinforced composites with constant cross-section. The properties of the composite produced with this process can compete with traditional steel and aluminum for strength and weight. The polymer reinforced matrix can be formulated to meet the most demanding chemical, flame retardant, electrical and environmental conditions (EPTA 2003).

The process involves pulling raw materials rather than pushing, as is the case in extrusion through a heated steel forming die using a continuous pulling device. The reinforcement materials are in continuous forms such as rolls of fiberglass mat and doffs of fiberglass roving. As the reinforcements are saturated with the resin mixture in the resin bath and pulled through the die, hardening of the resin is initiated by the heat from the die forming corresponding shape of the die (Strongwell 2003). While pultrusion machine design varies with part geometry, the basic pultrusion process concept is described in Figure 2-3.

Pultrusion can produce both simple and complex profiles eliminating the need for extensive post-production assembly of components. This process allows for optimized fiber architectures with uniform color eliminating the need for many painting requirements (Busel and Lockwood 2003).

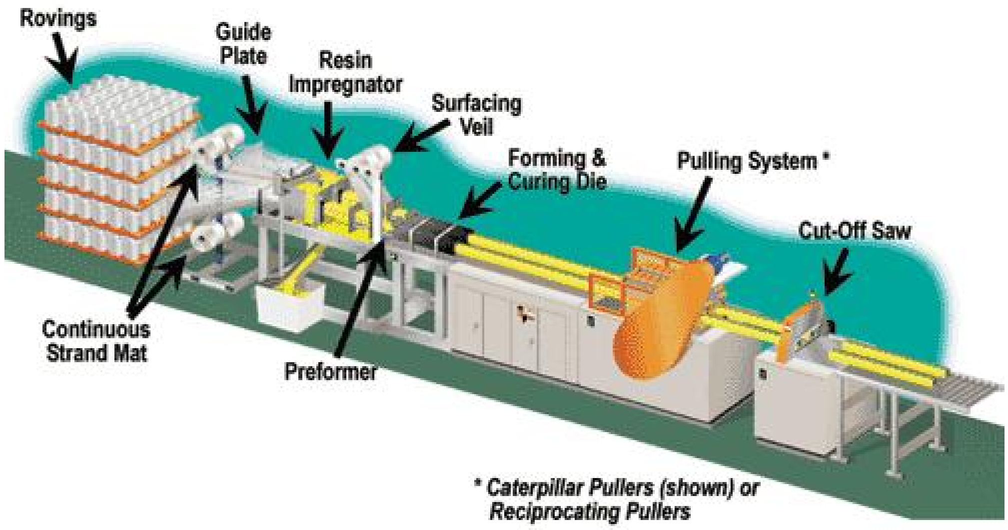

Figure 2-3 The Pultrusion Process (Source: Strongwell 2003)

2.4 Composite Manufacturer

The cost competitiveness of an FRP deck is typically project dependent and each FRP composite bridge deck manufacturer has its own system for the application. Following is the brief summary of characteristics of several leading FRP composite bridge deck manufacturers.

2.4.1 Creative Pultrusions, Inc.

Creative Pultrusions, Inc. (CP) was established in 1973. The company operates in two manufacturing locations: Alum Bank, Pennsylvania (Corporate Headquarters) and Roswell, New Mexico (CP 2003).

Superdeck of Creative Pultrusion (Figure 2-4) is a pre-engineered FRP composite bridge deck manufactured by the pultrusion process. Two profiles – double trapezoid (DT) hexagonal section (HX) is pultruded and bonded together to form bridge deck modules. The fiber architecture is composed of E-glass fibers in the form of multi-axial stitched fabrics, continuous roving and continuous fiber mats. The resin matrix is a weather-resistant vinyl ester resin.

Figure 2-4 Superdeck FRP Composite Panel (Source: FHWA)

2.4.2 Hardcore Composites

Hardcore Composites, founded in 1984, is the leading manufacturer of large-scale fiber reinforced polymer (FRP) composite materials for infrastructure applications. Its products, systems, and components include bridges and walkways, marine fender systems, and specialty composite stay-in-place concrete forms. Hardcore is famous for their specialty in the composite marine structures. Their customers include many state departments of transportation, port authorities, highway and marine contractors and specialty concrete repair contractors (Hardcore 2003).

In particular, Vacuum Assisted Resin Transfer Molding (VARTM) is used for the manufacturing process as seen in Figure 2-5. Hardcore has refined this process and developed an orthotropic honeycomb structural core to obtain the required structural properties and cost competitiveness. Hardcore currently operates out of a 108,000 sq. ft. facility in New Castle, Delaware.

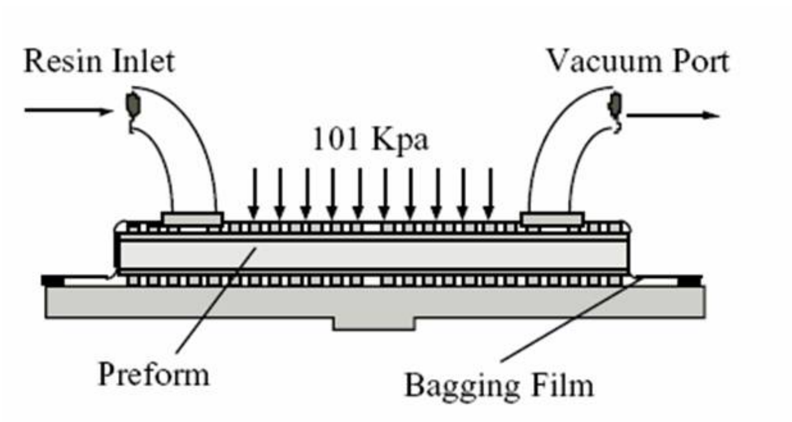

Figure 2-5 Vacuum Assisted Resin Transfer Molding (VARTM)
(Source: Smith et al. 2000)

2.4.3 Kansas Structural Composites, Inc.

Kansas Structural Composites, Inc. was formed in 1995 and they manufacture the fiber-reinforced polymer honeycomb (FRPH) sandwich panels. The company concentrates on applications for heavy-duty structural panels for the deteriorating highway infrastructure. KSCI built all fiber reinforced polymer (FRP) bridge on a public road on November 8, 1996 for the first time in U.S. over No-Name Creek, just three miles west of Russell, Kansas (KSCI 2003).

The use of fiberglass in FRPH sandwich construction produces a lightweight, corrosion-resistant panel that is relatively low in cost when compared to aerospace composite constructions. Even more, when considering the reduced costs of installation and public inconvenience, the cost of these panels can be favorably compared to more conventional construction materials. Prototypes can be built at costs of between \$3 and \$5 per pound (KSCI 2003).

Figure 2-6 Cross-Section of FRPH Deck Panel (Source: Busel and Lockwood 2003)

The fabrication for the most components of KSCI's bridge decks is completed by hand lay-up process method. Figure 2-6 shows cross-section of FRPH deck panel which is constructed by KSCI.

2.4.4 Strongwell

Strongwell claims to be both the world's largest pultruder of fiber reinforced polymer composites and North America's largest polymer concrete precaster. Strongwell has worldwide customer bases which include large industrial and commercial firms, major A&E's, leading contractors and distributors, and hundreds of other companies in a wide variety of markets. The company has three pultrusion manufacturing facilities in Bristol, Virginia, Washington County, Virginia and Chatfield, Minnesota.

Strongwell is actively involved in the advancement of FRP technology for civil infrastructure applications. Emerging applications for Strongwell's pultruded FRP products are pedestrian bridges and AASHTO HS-25 bridge superstructure, decks and guard rails. Strongwell manufactures a vehicular bridge deck (Figure 2-7) by combining pultruded square tubes and pultruded plate. The deck system can be designed for optimum performance depending upon design loads and stringer spacing. Tube sizes are typically 4”x1/4” or 6”x3/8” and plate thickness is typically 3/8” thick. The deck systems come complete with fastening hardware to allow positive attachment to steel, concrete of FRP bridge stringers (Strongwell 2003).

Figure 2-7 Strongwells’ FRP bridge deck (Strongwell 2003)

2.4.5 Martin Marietta Composites

Martin Marietta Composites (MMC) is one of the subsidiaries of Martin Marietta Materials (MMM), a national leader in the construction materials industry. MMC was founded by Martin Marietta Materials for the purpose of pursuing advanced material applications in bridges and infrastructures. The company’s customers include federal agencies, state and local transportation departments in approximately two dozen states (MMC 2003).

Martin Marietta Composites is located in Raleigh, North Carolina. The main product, *DuraSpan*® bridge decks, along with other structural composite products are manufactured in Sparta, North Carolina.

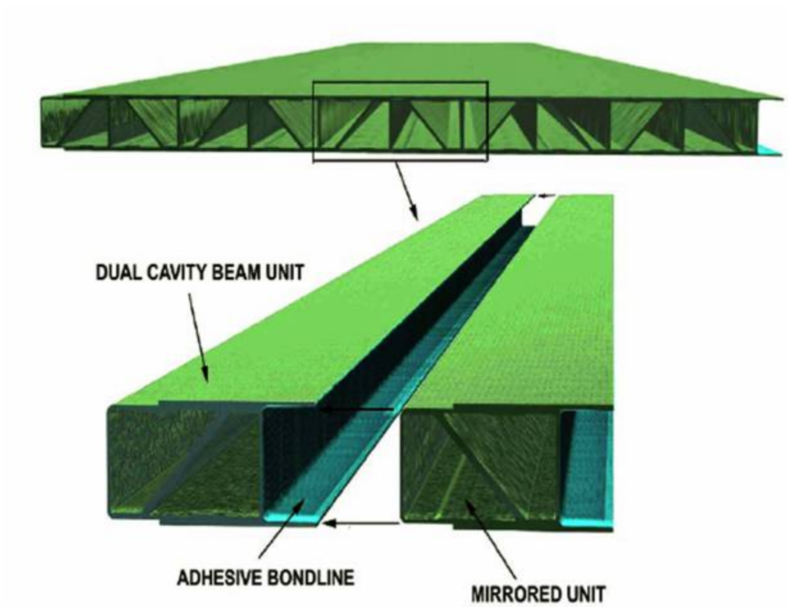

Figure 2-8 Schematic of MMC's DuraSpan FRP Deck Panel (Source: FHWA)

Martin Marietta Composites' FRP bridge deck is made of composite materials consisting of continuous fiber reinforcement of E-glass. The deck elements are formed through pultrusion in which fibers are wetted with the polymer resin and then pulled through heated metal dies, which at controlled temperatures and speeds causes the resin to cure (Busel and Lockwood 2003). Figure 2-8 shows Schematic of MMC's DuraSpan FRP Deck Panel. Panels are typically 8 to 10 ft. in width. The bonded panels are sent to finish shop, where all secondary work such as hole cutting and sealing, installation of closeouts, surface finishing and so on is performed. Panels are then shipped directly to the job site for installation (MMC 2003).

2.5 Previous analytical and experimental works on FRP bridge deck panels

FRP composite materials have been used successfully in other fields like aerospace, defense, and automobile industries. Even though there are a lot of database for their application, they may not directly be used for civil engineering applications. The reason is that there are critical differences in terms of load cycling, exposure to different environment, different service life and scale structure, and even the type of fiber and resin used as compared to FRP composites for civil infrastructure. Zureick et al. (1995) has emphasized such difference in operating conditions and configuration between bridge deck structure and aerospace application (Zureick et al. 1995).

- Exposure to moisture and ultraviolet
- Exposure to organic growths
- Continuous load cycling
- Long durations between inspection and maintenance
- Long service lives
- Large-scale structure
- Field joints and attachments
- Field assembly

Thus, it is increasingly becoming critical issues to convince their long-term durability in civil infrastructure after exposure to various environmental conditions during the expected service life of FRP composites. In this light, several studies have indicated the importance of their durability issues in civil infrastructure to enhance their application by structural designers and civil engineers (Stechkel et al. 1999; Karbhari 2003; Karbhari et al. 2003; Karbhari and Zhang 2003). Karbhari et al. (2003) identified seven specific environmental conditions (damage modes) leading to damage to FRP composites as an indicator of need for further collection, validation, and dissemination of data related to durability of FRP composites. The durability of a material or structure was defined as its ability to resist cracking, oxidation, chemical degradation, delamination, wear, and/or the effects of foreign object damage for a specified period of time, under the appropriate load conditions, under specified environmental conditions (Karbhari et al. 2003).

- Moisture/Solution effects
- Alkali effects
- Thermal effects
- Creep/relaxation effects
- Fatigue effects
- Ultraviolet (UV) effects
- Effect of fire

2.6 Installation procedure of FRP bridge deck panels by manufacturers

Construction procedure of FRP bridge deck panels by manufacturer varies from each other. In general, there are no uniform standards for installation and the manufacturer's own specification is used for installation. The following describes some similarities and differences in installation process between the manufactures.

2.5.1 HCI (Hardcore Composites Inc.)

Typical panels are shipped flat on standard semi-truck trailers. Panels are fabricated in as large as possible dimensions to reduce the number of field connections. Standard 1"-8 UNC lifting elements are molded into the panels to provide convenient picking. The picking weight and field orientation of each panel is provided with shipment of the panel (Hardcore 2003). Figure 2-9 shows overview of typical installation of a Single 20 ft. x 26 ft. Bridge Panel manufactured by Hardcore.

Figure 2-9 Installation of a Single 20 ft. x 26 ft. Bridge Panel (Source: Hardcore 2003)

Regardless of the type of construction, one-piece or multiple panels, each Hardcore structure is shipped with the specified embedment (Figure 2-10). These include lifting elements, guardrail attachments, attachments to the abutments and polymer concrete wearing surface and so on (Hardcore 2003).

Figure 2-10 Shipping of a Complete 39ft. x 17 ft. Panel (Source: Hardcore 2003)

Hardcore Composites has three types of design for deck connections. These are panel-to-abutment connections, panel-to-panel connections and panel-to-beam connections. When the FRP deck is self-supporting, the panels are connected to the abutments (see Figure 2-11). Connections are based on economically available anchor bolts. Match drilled holes through the panel to the abutment are typically specified at the fixed end. Slotted holes with a traditional expansion joint or a semi-integral approach slab can be detailed at the free end. In all cases, the anchorage is designed for factored loads and uplift forces in case of flooding.

Figure 2-11 Installation of 32 ft. x 13 ft. Longitudinal Panels on Abutments
(Source: Hardcore 2003)

For example, in the case of panel-to-panel connections, typical connections are designed using adhesively bonded butt joints or lap-splices (Hardcore 2003). The space between panels is completely filled with adhesive. Typically construction grade epoxy or marine grade methacrylate is used.

In particular, cellular core technology developed by Hardcore enables virtually unlimited three-dimensional fiber architecture. Curbs can be molded monolithically with the deck panel as a separate structure. For continuous curbs, scuppers are typically molded into the panel to provide drainage in the gutter (Hardcore 2003). Figure 2-12 shows typical installation of splice plates and bonded FRP Curbs.

Figure 2-12 Installation of Splice Plates and Bonded FRP Curbs (Source: Hardcore 2003)

In the case of guardrail connection (see Figure 2-13), guardrails are attached by either top-mounted or side mounted systems. For panels with a section depth of at least 8 inches, top mounted guardrails use embedded studs with adequate development length. For panels less than 8-inches thick, guardrails are attached by bolting through the deck and using a galvanized or stainless steel plate at the bottom face of the panel to distribute forces (Hardcore 2003).

Figure 2-13 Side-Mounted Guardrail on Vehicle Bridge (Source: Hardcore 2003)

2.5.2 MMC (Martin Marietta Composites)

Once the individual tubes have been pultruded, they are assembled into panels using a polyurethane adhesive. The width of panels are typically 8 to 10 ft. The bonded panels are sent to finish shop, where all secondary work such as hole cutting and sealing, installation of closeouts, surface finishing and so on is performed. Panels are then shipped directly to the bridge construction site for installation.

All MMC decks make use of composite bending-action with the girder using conventional shear studs and stirrups. Holes at the desired spacing for the connections are cut into the deck and foam inserts are placed inside the tubes to provide closed cavity. After that, shear studs are field welded when the deck panels are installed in place. Finally, grout is poured in the cavity of the deck. MMC has several methods of forming and pouring the haunches that are similar to conventional methods and have been accepted by various contractors and DOTs. Pouring of the haunches also needs to be performed after the panels are in place to ensure a uniform bearing surface (MMC 2003). Figure 2-14 shows typical liquid primer and epoxy paste being applied to the field joint.

Figure 2-14 Liquid Primer and Epoxy Paste to being applied the Field Joint
(Source: MMC 2003)

In the case of concrete barriers, the same method used for the deck-to-girder connections can be used to connect the deck to the reinforcing steel in the barriers. For steel guardrails (Figure 2-15), base plates for the rail posts are bolted through the deck or the guardrail may be cantilevered from the girders.

Figure 2-15 Steel Guardrail Cantilevered from Girders (Source: MMC 2003)

2.5.3 CPI (Creative Pultrusion Inc.)

The bridge deck arrives at the construction site in assembled modules approximately 8 ft. in width with the desired length. The modules weighs approximately

25 lbs/ft^2, including the polymer concrete wearing surface or 22 lbs/ft^2 without polymer concrete (CPI 2003). The bridge deck modules are usually lifted with nylon straps (Figure 2-16), four 3.5 in. x 6.25 in x 10 ft. long wood beams can be inserted into the hexagonal end sections for lifting the deck modules into position (CPI 2003).

Figure 2-16 Lifting Deck Panel Using Nylon Strap (Source: CPI 2003)

The deck modules are adhered with high-performance two-component polyurethane adhesive or equivalent. The components are applied from a bulk dispensing system. The mix ratios by volume of the adhesive are 3.5 resin to 1-part curative. Figure 2-17 shows typical application of adhesive to the connecting sections.

Figure 2-17 Application of Adhesive to the Connecting Sections

The deck modulus need to be positioned or moved within 50 minutes after the adhesive has been applied before it starts hardening. The working time will decrease with a rise in temperature and increase in lower temperatures. Typical duration of the installation for CPI's 6660 series deck panel is approximately 50 minutes. at 70ºF (CPI 2003).

The following procedure summarize the proper application of adhesive to the connecting sections (Busel and Lockwood 2003).

- First of all, apply a large bead of adhesive in the two radii sections of the bridge module truss.
- Second, apply a lard bead of adhesive at the edge of the truss flange. Third, apply a large bead of adhesive to the flat wall of the truss section in a sinusoidal pattern as shown in Figure 2-17. The horizontal distance between the peaks of the sinusoidal pattern shall not exceed 3 in.
- Finally, repeat the pattern applied on the bottom half of the truss section to the top half of the hexagonal component on the second deck module.

In addition, the following procedure outlines the proper installation of the deck modules at the construction site (Busel and Lockwood 2003).

- After applying the adhesive, locate the deck modules properly on the support beams.
- Position a minimum of two 6-ton hydraulic jacks per every 8 to 9 ft. of deck on the steel girders as shown in Figure 2-18.
- Apply even pressure in the plan of the deck by simultaneously jacking the deck module into the connected module.

- Jack the deck module into the receiving module until a gap is no longer visible between the two modules. For example, adhesive should flow from the ends of interface.
- Allow adhesive to set to the consistency of a rubber eraser and remove the excess with a putty knife.
- Repeat steps 1-4 until all deck modules are in place.

Figure 2-18 Joining Panels Together with Hydraulic Jacks (Source: CPI 2003)

2.5.4 KSCI (Kansas Structural Composites Inc.)

Many elements of the bridges are assembled at the factory to reduce the amount of field work required at the time of installation. Figure 2-19 shows a general overview of FRP composite bridge deck installation. The guardrail posts are inserted into the sockets of the edge closeouts and retained with one-inch solid pultruded dowels through the walls of each socket and the web of the post. The dowels are then protected with a vinyl ester resin. The posts, the synthetic wood standoff blocks, and FRP W-rail were drilled to accept one-inch FRP thread studs, which were secured with FRP nuts. This procedure eliminated the need to install railing at the site (KSCI 2003).

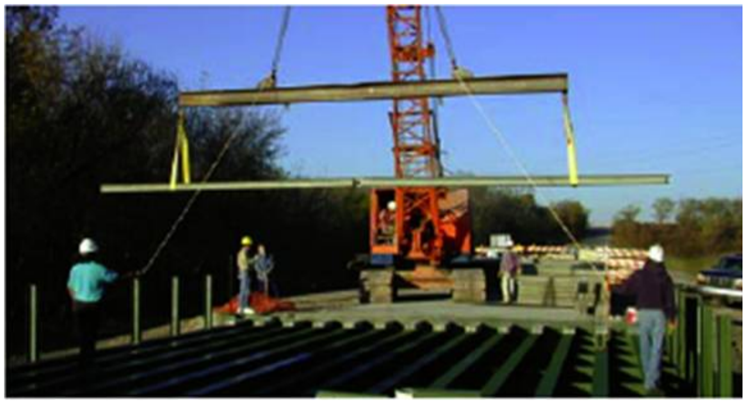

Figure 2-19 Installation of the KSCI's FRP Composite Deck (Source: KSCI 2003)

Figure 2-20 Bolting Down FRP Composite Deck (Source: KSCI 2003)

A primary bond is achieved by applying a wet laminate and vinyl ester resin to the lap joint flange on the bottom of the center section. The panel is then lifted and the joint is pulled together. To avoid scraping the wet laminate from the lap joint flange, the panel is suspended to hang with a five degree list. Chains are strung between the lift eyes of the center panel and the exterior panel. The panel is pulled into place until the joint is firm. Finally, the panel is lowered onto the header. In order to produce a optimal laminate thickness, upper side of the joint is overlaid with alternating layers of CSM and stitched roving. After this laminate had cured, the joint is filled with polymer concrete to match the level of the wear surface (KSCI 2003). Figure 2-20 shows bolting down FRP Composite Deck at the construction site.

2.6 Challenges and Technical Issues in their application

There are many challenges in the application of FRP composite materials. Those challenges should be considered as an opportunity to improve the materials to ensure that the final product will be durable and reliable.

First of all, the main concern with FRP composite materials is the long-term durability since the sufficient historical performance data are not available in bridge applications. For example, there is a concern among bridge engineers for the long-term integrity of bonded joints and components under cyclic fatigue loading. There are also concerns with improper curing of the resins and moisture absorption and/or ultraviolet light exposure of composites that may affect the strength and stiffness of the structural system. Certain resin systems are found ineffective in the presence of moisture. In the case of a glass fiber composite, moisture absorption may affect the resin and allow the alkali to degrade the fibers. Therefore, there is much work to be done in developing well-designed anchorages, connection details, and bonded joints in composites for long-term durability (Tang and Podolny 1998).

Secondly, even though FRP composites have a higher tensile strength over conventional materials, the design has been focused on the stiffness requirement rather than strength. There is still much room for improvement and advancement of the composite deck systems in order to capitalize on its material strength. The key to successful application of the deck superstructure system is to optimize its geometric cross section and to establish well-defined load paths (Tang and Podolny 1998).

Finally, in order to maintain and take advantage of favorable characteristics of FRP composite bridge deck, more desirable and practical research is needed to increase demand and application. More efficient manufacturing and effective production methods should be explored and developed in terms of cost efficiency. Moreover, marketability, constructability, maintainability, and operability of FRP bridge deck panels should be supported by the continuous future research works.

In a summary, the following technical needs and concerns should be address: (i) development of design standards and guidelines; (ii) efficient design and characterization of panel-to panel joints and attachment of decks to stringers; and (iii) economical engineering of cost analysis.

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CHAPTER 3: PRELIMINARY DATA COLLECTION AND DATA ANALYSIS (QUESTIONNAIRE SURVEY)

3.1 Introduction

As mentioned in Chapter-1, preliminary data for this research were collected through a series of questionnaire, case studies, and personal interviews. The purpose of this survey was to collect subjective and objective data with regard to constructability, maintainability, operability of FRP (Fiber Reinforced Polymer) bridge deck panels. Also, information was collected with respect to the fabrication, construction methods, quality, safety, man-hour requirements, cost and productivity issues, as well as the skill level required in order to develop standard construction guidelines for FRP bridge deck construction. Questionnaire-I assisted the research team in identifying a set of criteria that were important to establish the state of the art (research and development) and also state of practice of fabrication and use of composite bridge decks both in new bridge and in rehabilitation projects. This chapter illustrates the analysis of the data obtained from questionnaire survey-I.

3.2 Questionnaire Survey

The questionnaire survey was sent to the bridge engineers of 52 State Departments of Transportation (DOTs) using regular mail or e-mail. As shown in Figure 3-1, 47 out of 52 DOTs (90%) responded to the questionnaire. The questionnaire is composed of four parts: (1) General information of FRP bridge deck panels, (2) Constructability of FRP bridge deck panels, (3) Maintainability and operability of FRP bridge deck panels, and (4) Life cycle cost (LCC) of FRP bridge deck panels. A copy of the questionnaire survey is attached in appendix A.

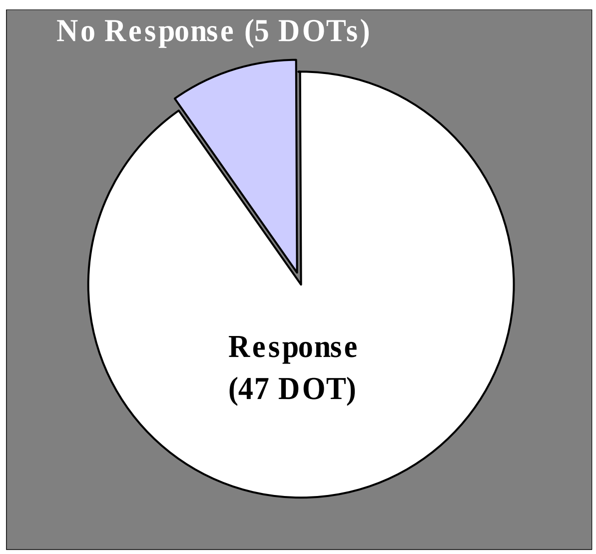


Figure 3-1 Number of DOTs responding to the questionnaire survey

3.1.1 General information of FRP bridge deck panels

According to the results of the questionnaire survey, a total of 9 DOTs have currently used FRP bridge deck panels among 47 DOTs responding to the questionnaire survey (Figure 3-2). In Figure 3-2, sections marked 1 and 2 along X axis represent DOT currently using FRP bridge deck panels and DOT currently not using FRP bridge deck panels, respectively. The information posted by FHWA helped a research team in identifying DOTs currently using FRP bridge deck panels among DOTs not resending to questionnaire survey.

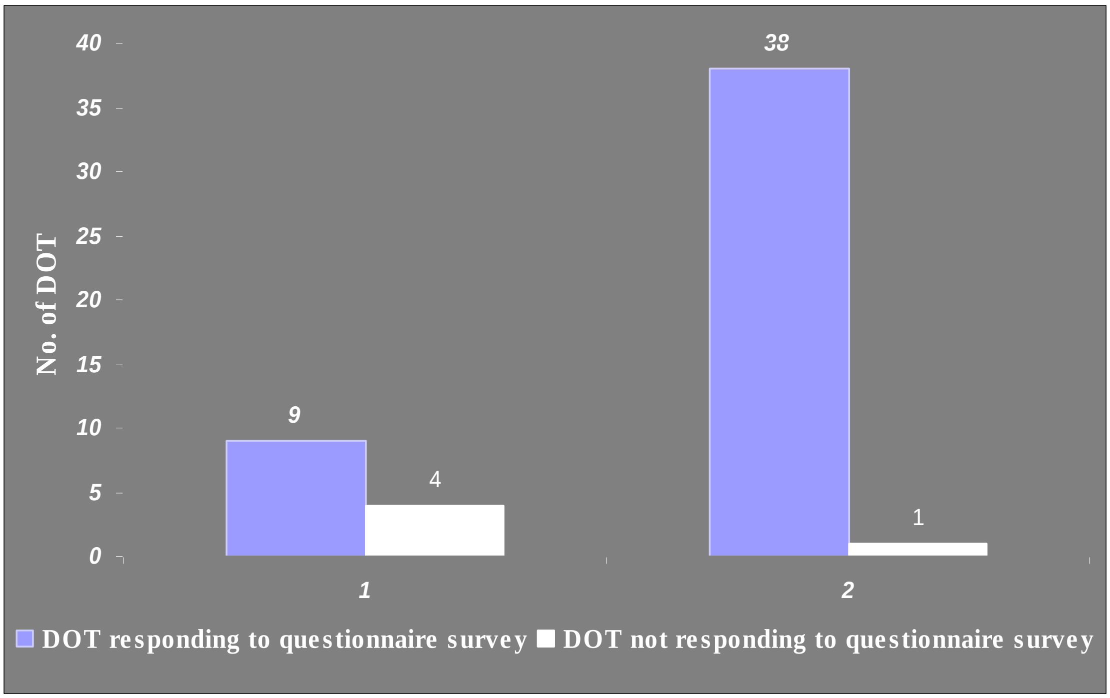


Figure 3-2 DOT currently using or not using FRP bridge deck panels

However, according to the information posted by FHWA on "Current practices in FRP composite technology" several FRP bridge deck construction projects have been completed by 17 DOTs (*Current* 2003). The 17 DOTs are as follows

- California
- Delaware*
- Idaho
- Illinois*

- **Iowa****
- Kansas*
- Maryland*
- **Missouri****
- New York*
- North Carolina*
- Ohio*
- Oregon*
- Pennsylvania*
- South Carolina
- **Virginia****
- West Virginia
- **Wisconsin****

It was interesting to note the difference between the FHWA information and that obtained through the questionnaire. Based on the results of the questionnaire survey, the 9 DOTs listed among group-1 in Figure 3-2 are marked with an (*), whereas, the 4 DOTs marked with (**) responded to the questionnaire survey as "They currently do not use FRP bridge deck panels". The differences in response are listed below:

Iowa DOT

- FHWA web-info.
    - The '53rd Avenue over Crow Creek' project located in Bettendorf, Iowa was completely finished in 2001 by Martin Marietta

Composites (MMC), one of the manufacturers producing FRP bridge deck panels.

- Questionnaire Survey
    - The design of the first FRP deck is underway. One bridge deck has been scheduled for installing FRP bridge deck panels within 5 years.
    - The criteria for selecting FRP bridge deck panel application include: (1) ease of installation (2) ease of transportation, and (3) less sensitive to environmental conditions.

Missouri DOT:

- FHWA web-info.
    - The ‘City of St. James’ project was completely finished by Kansas Structural Composites Inc.,(KSCI), one of the manufacturers producing FRP bridge deck panels.
- Questionnaire survey
    - The Missouri Department of Transportation has not installed any FRP decks on state maintained routes. The city of St. James Missouri has used FRP deck panels on three structures. Dr. Antonio Nanni of the University of Missouri – Rolla can provide additional details.
    - Three structures were installed in the local jurisdiction of the city of St. James, Missouri. The installation of these structures was part of an

experimental program to determine the viability of FRP bridge deck panels

Virginia DOT:

- FHWA web-info.
    - Troutville Weigh Station (Strongwell)
    - Tom's Creek Bridge, Blacksburg, VA (Strongwell)
    - Icky Cr, Sugar Grove, VA (Strongwell beams, timber deck)
- Questionnaire survey
    - Troutville weigh station: This project was completed by Strongwell Corp. VDOT allowed the FRP deck system to be placed into the ramp at the weight station. The project was monitored by Professor Tommy Cousins from Virginia Tech University for Strongwell. VDOT also provided Richard T. Brown from Atlantic Research Corporation the same access to do FRP research.
    - Tom's Creek Bridge, Blacksburg, VA and Icky Cr, Sugar Grove, VA: The two projects involved FRP beams but with a timber deck and asphalt riding surface.
    - Within 1 year, FRP bridge deck panels will be scheduled for installation as part of an Innovative Bridge Research and Construction (IBRC) project.
    - The criteria for selecting a bridge for FRP bridge deck panel application for the Innovative Bridge Research and Construction (IBRC) program

noted above was to increase the posted weight limit. Funds are allocated for the program by the FHWA annually. State DOT's submit their projects for consideration. One of the projects put forward by VaDOT that will receive funds is to replace the existing deck on a truss span with an FRP deck so that the posting limit could be raised.

Wisconsin DOT

- FHWA web-info.
  - US-151 / Hwy 25 (Composite Deck Solution (CDS) hybrid deck system)
- Questionnaire survey
  - The design of the first FRP deck is underway.
  - The CDS system is similar to one method of conventional concrete bridge deck construction, except that FRP is used to replace steel.

<u>3.1.1.1 Reasons for not using FRP bridge deck panels to date</u>

Even though the FRP bridge deck panels have a lot of advantage over conventional bridge deck, the acceptance of FRP bridge deck panels has been conspicuously slow. The bridge engineers were asked why their DOT has not used FRP bridge deck panels. The summary of their opinion is as follows:

- ❑ Want to see more reliable performance data before using them.
- ❑ Too expensive, unproved durability, lack of detail

- Not familiar with design criteria. Once installed, what condition inspection criteria and repair procedures would be used?
- There is no specification for their design or acceptance by AASHTO.
- Not comfortable with this technology. No research associated with that.
- Lack of supplier and installers in the area.
- Washington DOT: They don't view FRP deck panels as economically viable alternatives to conventional reinforced concrete decks for standard bridge applications.

Based on the questionnaire responses, most of the respondents currently considered high initial cost to be the main disadvantage of FRP bridge deck panel application. A few respondents were concerned of the maintenance issues after their installation. Another obstacle for the application of FRP bridge deck panels was lack of reliable performance data to prove their long service life. The respondents from Hawaii, Georgia, and Washington DOT indicated that the application of FRP bridge deck panels was not yet cost effective and appropriate for their requirements. The respondents from Texas DOT indicated lack of crash tested railing attachments for FRP bridge deck panels as a hindrance to their application. Whereas, Arkansas DOT indicated that they have not been asked to use the panels but they may be receptive if a contractor would make a request or there is an otherwise clear advantage to use them for a particular application.

3.1.1.2 The schedule for future application

Among the State DOTs responding to the questionnaire survey, only three out of thirty eight State DOTs currently not using FRP bridge deck panels have plans for installing FRP bridge deck panels within five years.

Table 3-1 The schedule for future application

	DOT	Plan	No Plan
DOTs currently not using FRP bridge deck panel	Iowa	1	
	Virginia	*	
	Vermont	1	
DOTs currently using FRP bridge deck panel	New York	5 – 10	
	Ohio	2	
	Pennsylvania	1	
	Illinois	1	
	North Carolina		√
	Kansas	3	
	Delaware	N/A	
	Maryland		√
	Oregon	1	

Note: * Within 1 year, FRP bridge deck panels will be scheduled for installation as part of an IBRC project.

As presented in Table 3-1, Delaware State DOT does not know yet whether they can use them in the near future or not and only two State DOTs have no plan to use them within five years. The number of projects scheduled in the rest of the State DOTs range from one to ten. Especially, in case of New York DOT, five to ten projects using those panels will be scheduled and Kansas State DOT has three scheduled projects within next 5 years. One of the important finding of the questionnaire was that only eight percent of the State DOTs that do not currently use FRP bridge deck panels would like to use them.

3.1.1.3 Advantages of FRP bridge deck panels

In the questionnaire the respondents were asked to prioritize the advantages of FRP bridge deck panels using a scale of 1-5, where 1 represented "least priority" and 5 represented "top priority" (Figure 3-3). The advantages of FRP bridge deck panels are marked A-E on the horizontal axis in Figure 3-3, where (**A)** Increased capacity for live load with possible elimination of weight restrictions, (**B**) Good durability, fatigue resistance, long service life, resistance to de-icing salts, (**C**) Fast installation due to modular, prefabricated nature, and reduced traffic delay, (**D**) Cost saving, less expense for maintenance than total replacement, and (**E**) Less environmental impact and fewer permits required than replacement.

According to several previous studies, FRP composite materials can not only extend service life but also reduce maintenance costs thereby improving life cycle cost efficiency (Zhou et al. 2001, Ehlen 1999, Ehlen 1997, Yost and Schmeckpeper 2001). However, as shown in Figure 3-3, bridge engineers responding to the questionnaire survey doubted somewhat that FRP bridge deck panels could offer cost saving in terms of less expense for maintenance than total replacement. Nystrom et. al. (2003) identified in their study that FRP bridge technology would not be cost competitive, even in the standard short-span bridges, if the cost of component materials does not reduce significantly. Therefore, it is imperative to reduce cost of FRP components in the application of FRP bridge deck panels.

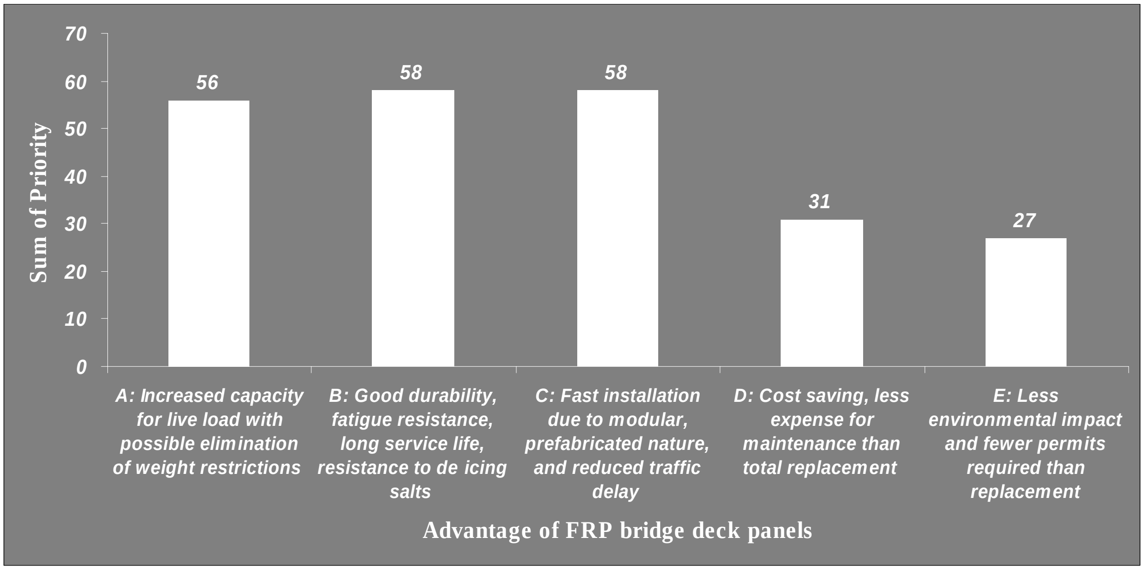


Figure 3-3 Advantage of FRP bridge deck panels

3.1.1.4 The Application of FRP bridge deck panels

As shown in Figure 3-4, 8 out of 9 DOTs currently using FRP bridge deck panels have used them in low-volume-rural roadways. Delaware and Ohio DOT have also used them on high-volume–rural roadways. FRP bridge deck panels have also been installed on lift span (movable bridge) by Martin Marietta Composites, Inc., at Astoria, Oregon. It is the first application of its kind in the United Sates where the existing wood or timber decking on a movable bridge was replaced by FRP bridge deck panels.

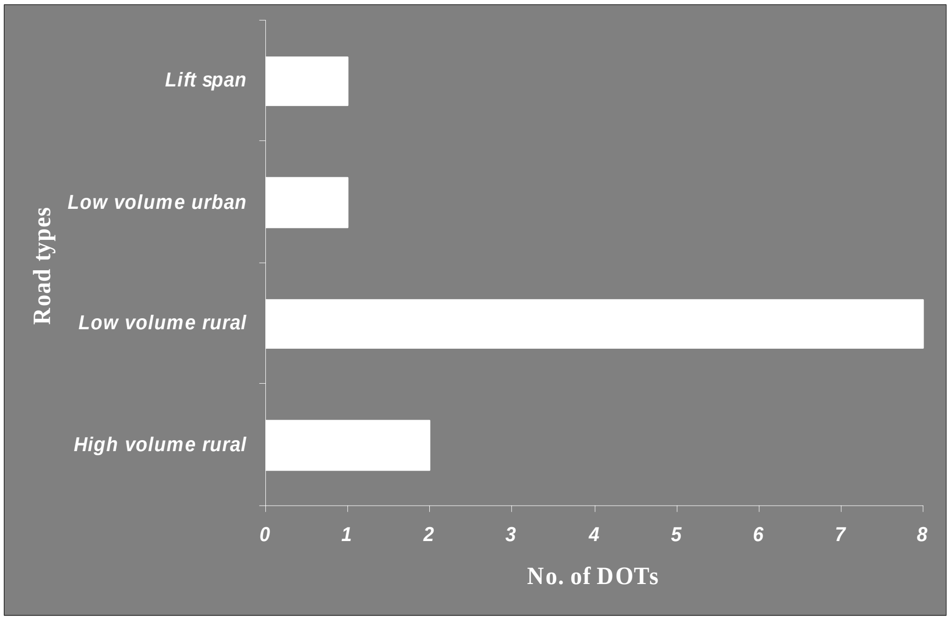


Figure 3-4 Road type of application for FRP bridge deck panels

3.1.2 Construability issues of FRP bridge deck panels

In this section, the following issues with regard to construability of FRP bridge deck panels are introduced.

- ❑ Deck structure types
- ❑ Construction sequence/method
    - For connection of FRP bridge deck panels
    - For connection of deck-to-girder,
- ❑ Wearing surface
- ❑ Specific installation method
- ❑ Manufacturing processes
- ❑ FRP bridge deck cross-section types
- ❑ Construction specifications

- ❑ Detailed information on completed project (i.e., project name, location, date installed, etc.)
- ❑ Barriers encountered in installing
- ❑ Delivery issues

3.1.2.1 Deck structure types replaced

FRP bridge deck panels have been predominantly used to replace ‘Concrete Cast-in-place’ and ‘Wood or Timber’ deck structures as shown in Figure 3-5. According to the results of the questionnaire survey, FRP bridge deck panels could be used to replace various types of deck structure.

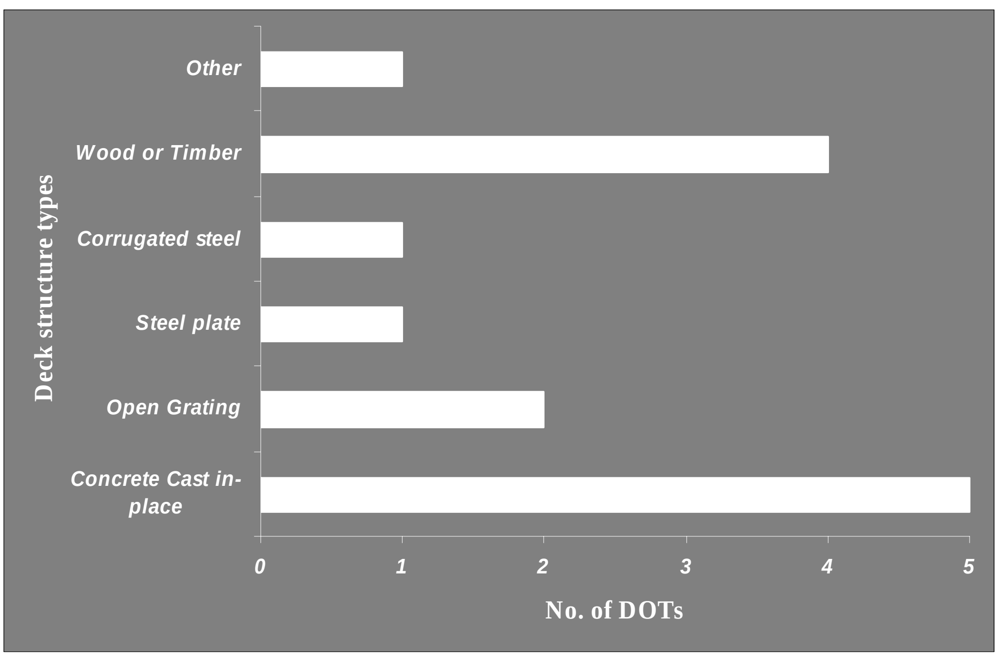


Figure 3-5 Deck structure types

3.1.2.2 Construction sequence/method for connection

Based on the results of the questionnaire survey, a total of 5 manufacturers' FRP bridge deck panels have been installed. In this section, the information on construction sequence/method to connect those panels and decks to girders is discussed. However, the sequence might change a little according to the project requirements.

(1) For connection of FRP bridge deck panels

- *Martine Marietta Composites (MMC)*: Typical panel-to-panel connections are made by applying epoxy adhesive in the tongue-and-groove and then holes are drilled through both sections and FRP dowel bars are placed in the hole. The dowel bars are installed to protect the joint while the epoxy adhesive cures. As a last step, FRP splice strips are installed over the field joints for additional durability (Refer to Figure 3-6).

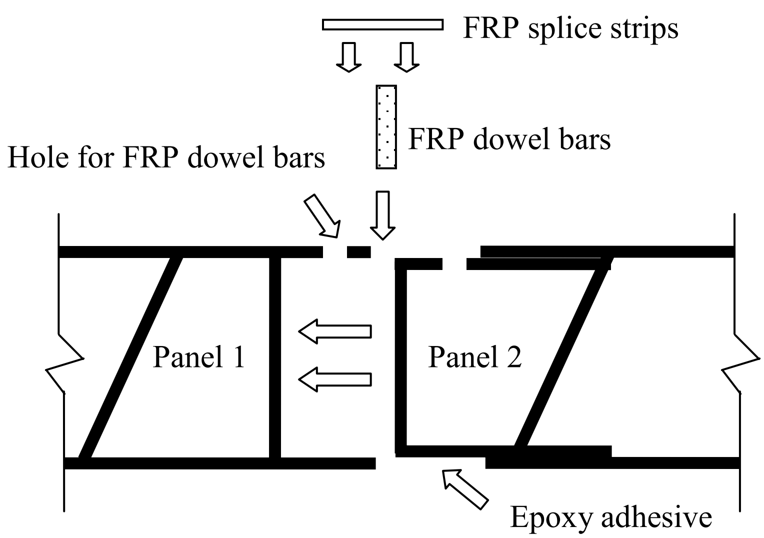


Figure 3-6 MMC joint system

- <u>*Hardcore Composite Inc.,(HCI)*</u>: The panels are connected by using epoxy adhesive in the tongue-and-groove and FRP splice plate are installed over the filed joints for additional durability (Refer to Figure 3-7).

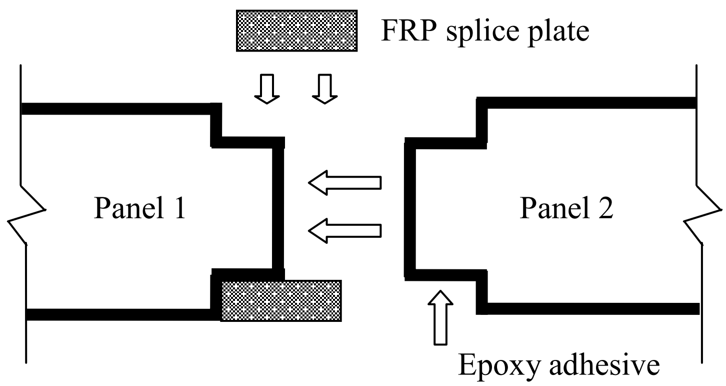


Figure 3-7 HCI joint system

- Kansas Structural Composites Inc., (KSCI): The panel-to-panel connection method is somewhat similar to that of HCI except for using *bolts and nuts* instead of FRP splice plates.
- Creative Pultrusion Inc., (CPI): The deck modules are connected with polyurethane adhesive in the tongue-and-groove (Refer to Figure 3-8).

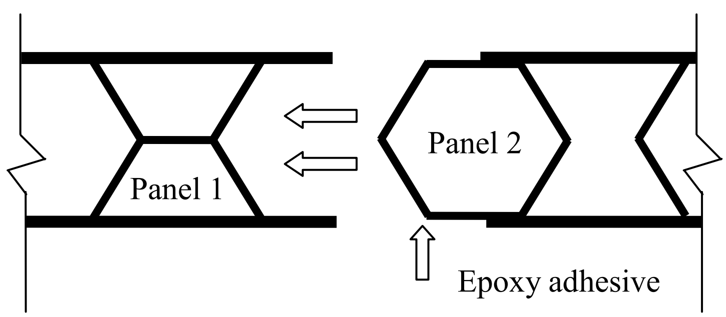


Figure 3-8 CPI joint system

- Infrastructure Composites International (ICI): Pilogrip adhesive is used to connect the male and female ends of adjacent panels together (Refer to Figure 3-9)

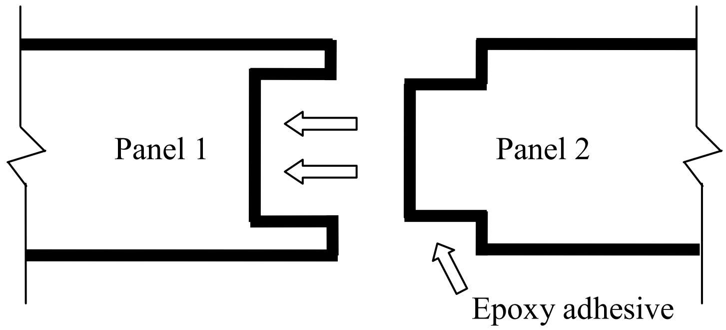


Figure 3-9 ICI joint system

The questionnaire survey indicated that cracks were generated in the field joints of FRP bridge panels for all the manufacturers. It is apparent that manufacturers should improve the construction method for applying field joints to prevent these cracks. As shown in Figure 3-10, the deck connection of MMC has been used most up to now.

- Missouri DOT: KSCI
- New York DOT : MMC and HCI
- Ohio DOT: HCI, MMC, ICI, and CPI
- Oregon DOT: MMC
- Pennsylvania DOT: MMC, HCI, and CPI
- Illinois DOT: MMC
- North Carolina DOT: MMC
- Kansas DOT: KSCI
- Delaware DOT: HCI
- Maryland DOT: MMC

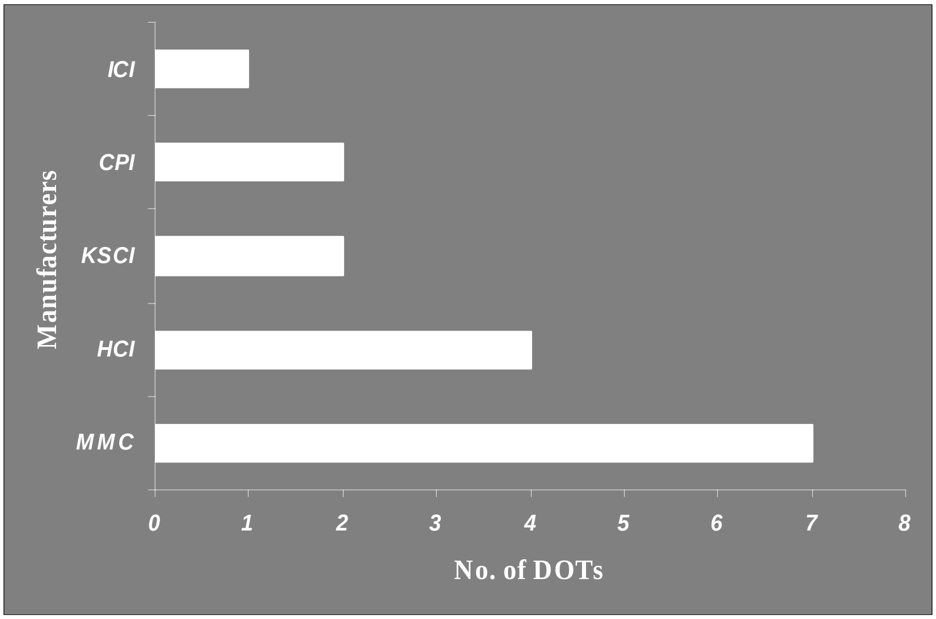


Figure 3-10 Construction method for deck connection

(2) For connection of deck-to-girder (**Busel and Lockwood 2000)**

- MMC: After the decks of MMC are in place, they are connected with the girders by using shear studs (Figure 3-12 (a)) Holes are cut into the deck for connection in the factory. As shown in Figure 3-12 (c), the shear studs are welded into the girders using a shear stud gun and then non-shrink grout is poured in the cavity as shown in Figure 3-12 (d).

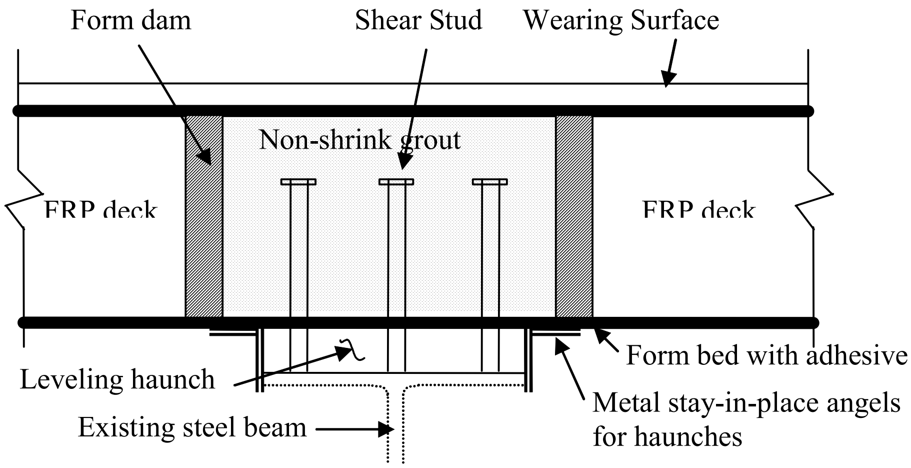
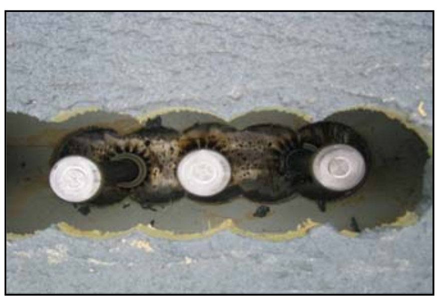


Figure 3-11 MMC deck-to-girder system

(a) Ready to use shear studs



(b) After welding shear studs

(c) Shear stud gun

(d) Non-shrink grouting

(e) After non-shrink grouting

Figure 3-12 MMC deck-to-girder system's pictures

- HCI: As shown in Figure 3-13, in the deck-to-girder connection, studs are welded into the concrete beams through predrilled stud-holes in each of the panels. The studs are welded to the steel embedded in the deck and to the steel plates embedded in the concrete beam. Finally, non-shrink grout is poured in the cavity

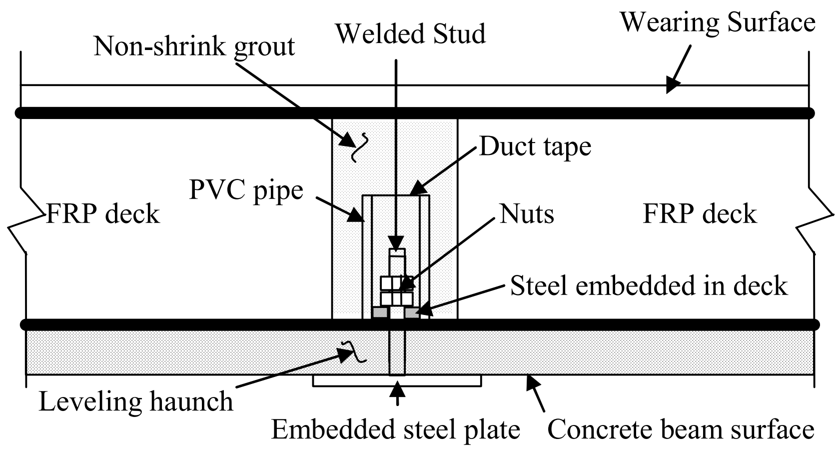


Figure 3-13 HCI deck-to-girder system

- KSCI: To connect deck-to-girder, blind fasteners are used at the joints. Blind fasteners require access from only one side of the work piece when they are installed. Polymer concrete is poured to fill the joints.
- CPI: Unlike other manufacturers, CPI uses spacer wedges instead of a haunch in order to achieve the desired cross slope. The FRP bridge deck panels are placed on top of the spacer wedges and the shear studs are welded into the existing steel girders through predrilled stud-holes in each of the panels. Two cardboard bulkheads are inserted into the deck section in order to make cavity to grout and then non-shrink grout is poured in the cavity (Refer to Figure 3-14)

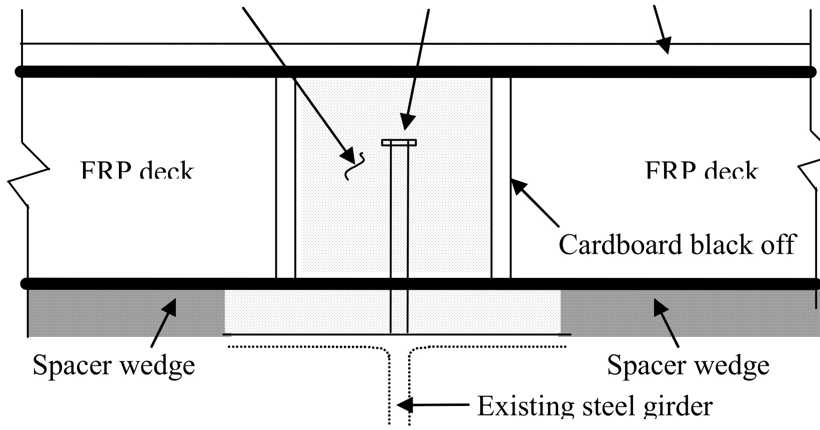


Figure 3-14 CPI deck-to-girder system

- ICI: Once the panels are in place, shear studs are welded into the girder flanges through predrilled holes in each of the panels. A plastic cylinder is inserted into the holes in order to make cavity for the grout and then non-shrink grout is poured into the cavity.

3.1.2.3 Wearing surface

Bituminous material was predominantly used as the material for the wearing surface for FRP bridge deck panels followed by polymer concrete, epoxy overlay, and latex modified concrete (Figure 3-15). For example, 'HOT Bituminous asphalt' and 'Basalt aggregate' was used in Pennsylvania DOT. The wearing surface product applied by Pennsylvania DOT was 'T-48' made by Transpo Industries Inc.

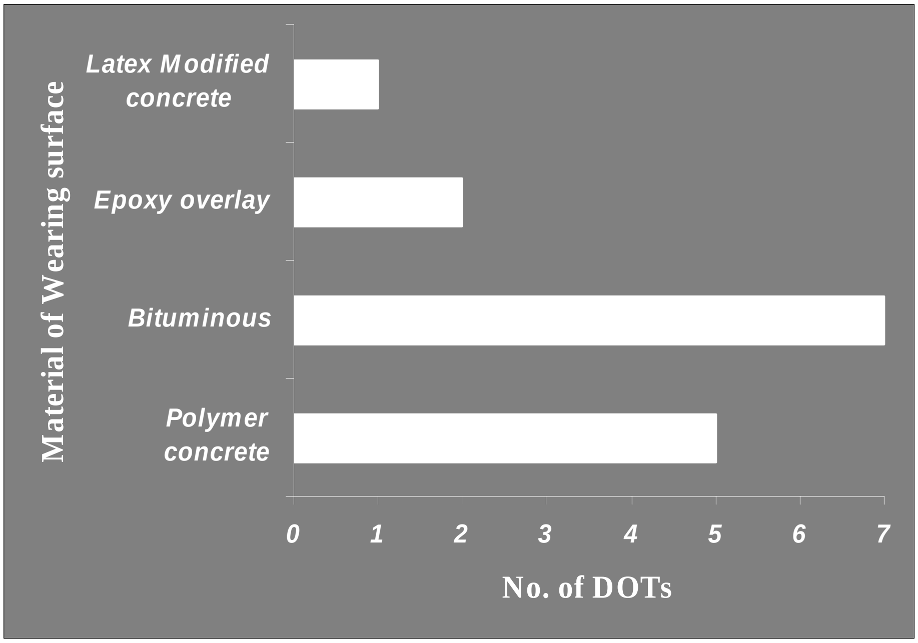


Figure 3-15 Material types of wearing surface

3.1.2.4 Specific installation method

The DOTs that responded to the questionnaire indicated that they do not have a specific method of FRP bridge deck panel installation but they followed the installation method recommended by the manufacturer selected for their projects.

3.1.2.5 Manufacturing processes

The following is a summary of manufacturing methods used by different DOTs for FRP bridge deck panels

- Missouri DOT: Open molding (Hand Lay-up)
- NY DOT: Open Molding (Hand Lay-up), Closed Molding (Pultrusion and Vacuum Assisted Resin Transfer Molding)

- Ohio DOT: Open Molding (Hand Lay-up), Closed Molding (Pultrusion and Vacuum Assisted Resin Transfer Molding: VARTM)
- Pennsylvania DOT; Open Molding (Hand Lay-up), Closed Molding (Pultrusion and Vacuum Assisted Resin Transfer Molding)
- Illinois: Closed Molding (Pultrusion)
- North Carolina DOT: Closed Molding (Pultrusion)
- Kansas DOT: Open Molding (Hand Lay-up)
- Delaware DOT: Close Molding (Vacuum Assisted Resin Transfer Molding: VARTM)
- Maryland DOT: Close Molding (Pultrusion)
- Oregon DOT: Close Molding (Pultrusion)

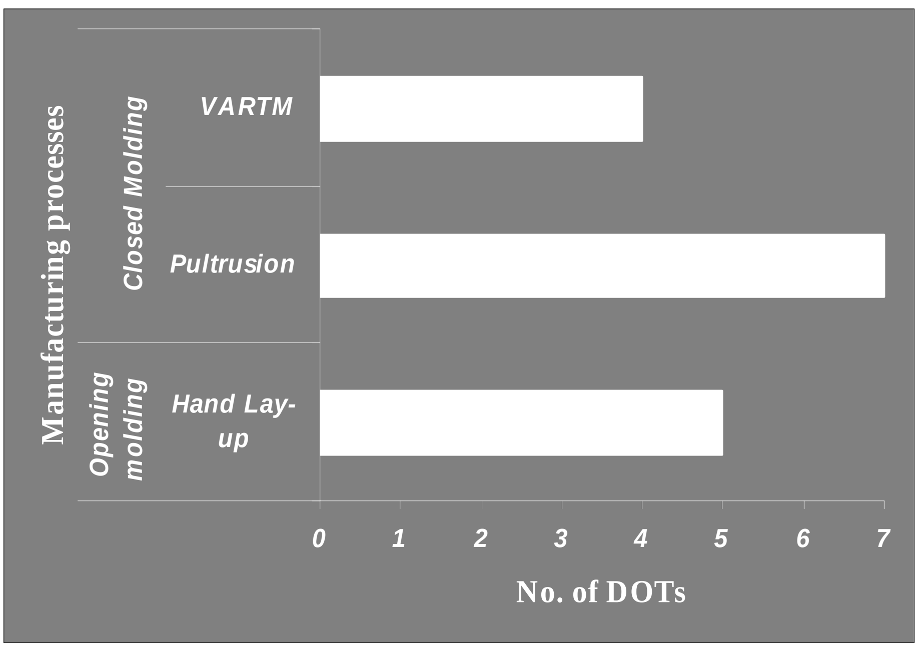


Figure 3-16 Manufacturing processes

The ‘Pultrusion’ processing method was used by 7 DOTs and is directly related to the manufacturing process used by the selected manufacturer (also refer to Figure 3-10).

As explained in Chapter 2, Martin Marietta Composites (MMC) and Creative Pultrusion Inc., (CPI) use ‘Pultrusion’ method whereas Hand lay-up method is used by Hardcore Composites Inc., (HCI) and Kansas Structural Composites Inc., (KSCI). Vacuum Assisted Resin Transfer Molding (VARTM) method has also been used by HCI.

3.1.2.6 FRP bridge deck cross-section types

According to a study by Zureick et al. (1995), the performance of several FRP bridge deck panel configurations was tested using a general-purpose finite-element code, Structural Analysis software (SAP) IV in the preliminary studies (Henry 1985, Ahmad and Plecnik 1989, Plecnik and Azar 1991). The SAP utilizes the finite element method to calculate the response of a structure such as displacement, stress, strain, moment, etc. The finite element method is one of the most popular structural analysis methods using computers. From the preliminary studies it was found that the design was always controlled by the deflection limit state rather than the strength limit state.

The results of these preliminary studies indicated that type ‘A’ of Figure 3-17 had the lowest deflection limit as compared to other cross-section types. According to the studies by Henry (1985) and Ahmad and Plecnik (1989), deflection limit (stringer spacing/800) was satisfied when the thickness of top, bottom, and diagonal member were 5/8 in., 1/2 in., 3/8 in., respectively with a height of 9 in. as shown in Figure 3-17 (Zureick et. al. 1995).

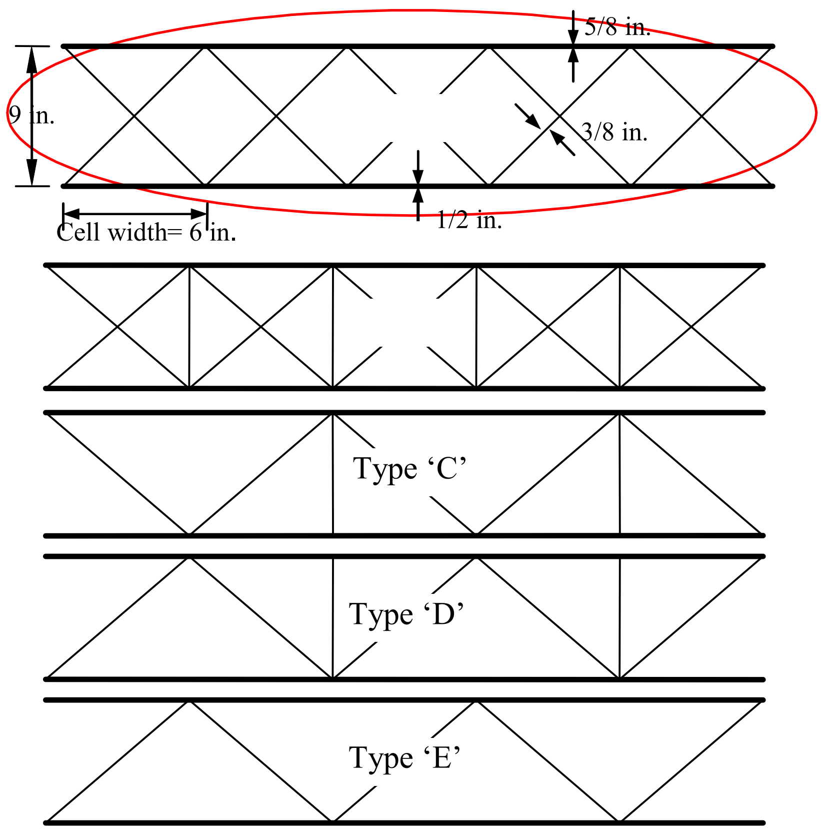
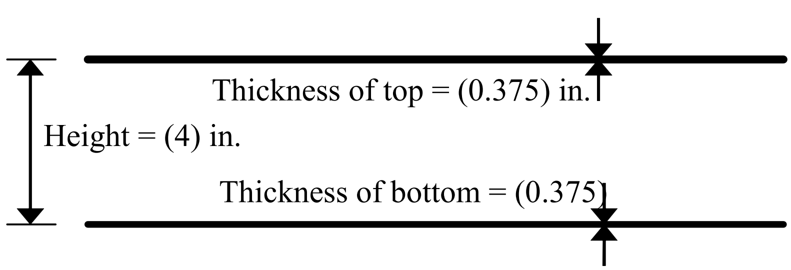


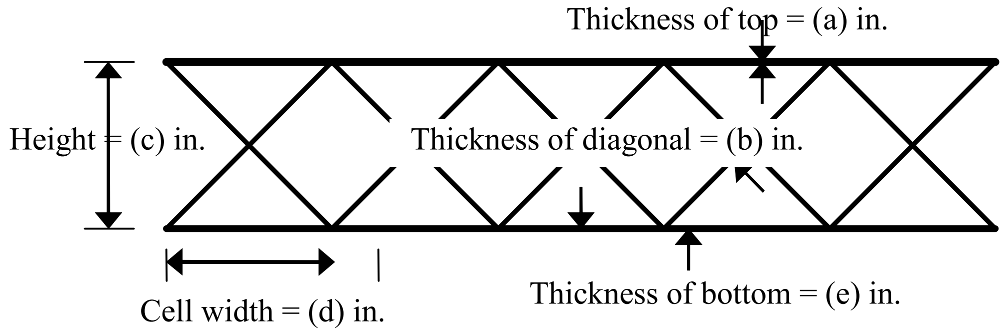
Figure 3-17 FRP bridge deck cross-section types

In order to identify the cross-section types and the thickness used by different states the following questions were asked in the questionnaire: (i) What is the thickness of top, bottom, and diagonal plates of the FRP bridge cross-section types used in your state? (ii) Please indicate the cross-section types used in your state? The summary of the responses is as follows:

- ❑ Missouri DOT: Honeycomb or Vertical sine-wave type

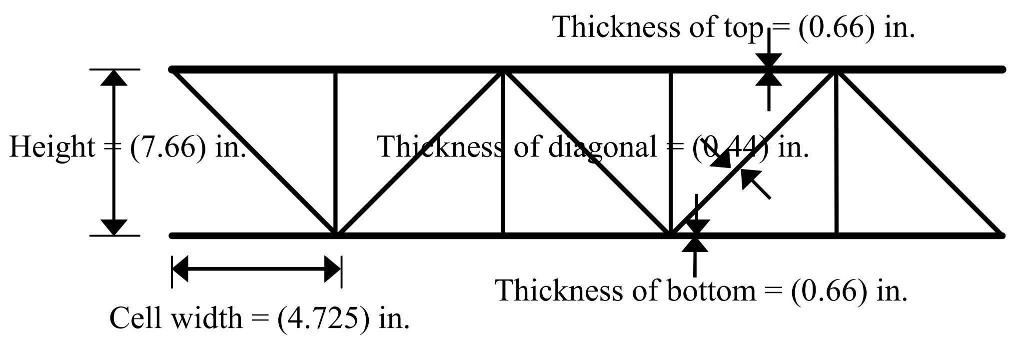


- Pennsylvania DOT: Honeycomb or Vertical sine-wave type (Bridge 1), Box-type, and Hexagon-type

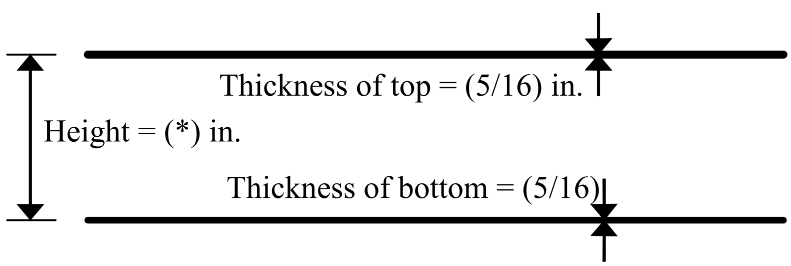


	Bridge 2	Bridge 3	Bridge 4
a	0.66	0.75	0.80
b	0.44	0.167	0.44
c	7.66	8.0	7.66
d	0.5	11.938	6.33 – 4.71
e	0.66	0.75	0.8

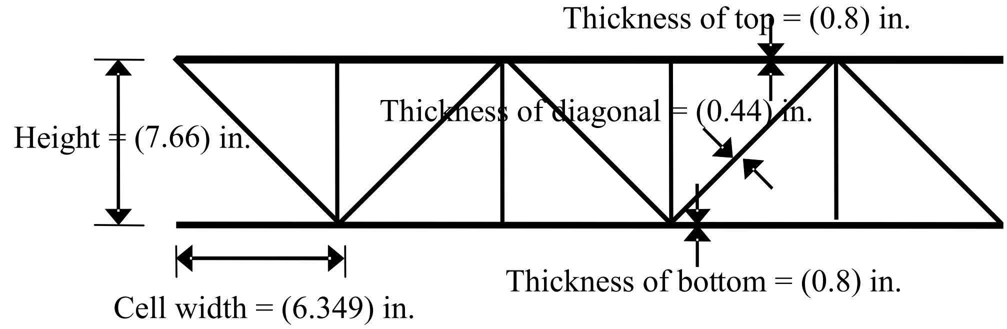
- North Carolina DOT: Box-types



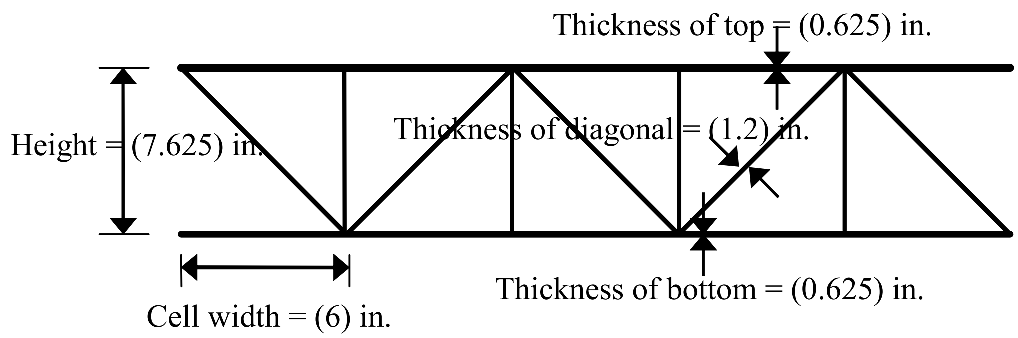
- Kansas DOT: Vertical sine-wave type (*:4 ¾ in. – 22.5 in.)

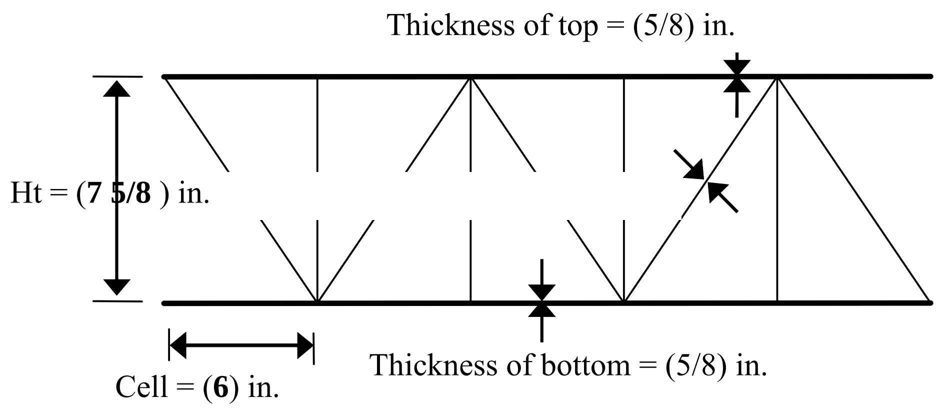


- Maryland DOT: Box-types



- Oregon: Box-types





3.1.2.7 Construction specifications

Respondents were asked to indicate the construction specifications of FRP bridge deck panels such as standard specification, warranty issues from manufactures and

FHWA, deflection limit, design load, etc. None of the responding DOTs had a standard construction specification for FRP bridge deck panels. Only job specific specifications were used. Two respondents indicated that they had a warranty from the suppliers.

- ❑ Pennsylvania DOT: 2 years warranty on FRP superstructure from Hardcore Composite Inc.
- ❑ Delaware DOT: Warranty of FRP bridge deck panels

Six respondents answered to the question with regard to design load. As shown in Figure 3-18, New York and Pennsylvania DOT had a design load HS 25 as compared to HS 20 in four DOTs and the deflection limit ranged from L/500 to L/800 (L: Stringers spacing).

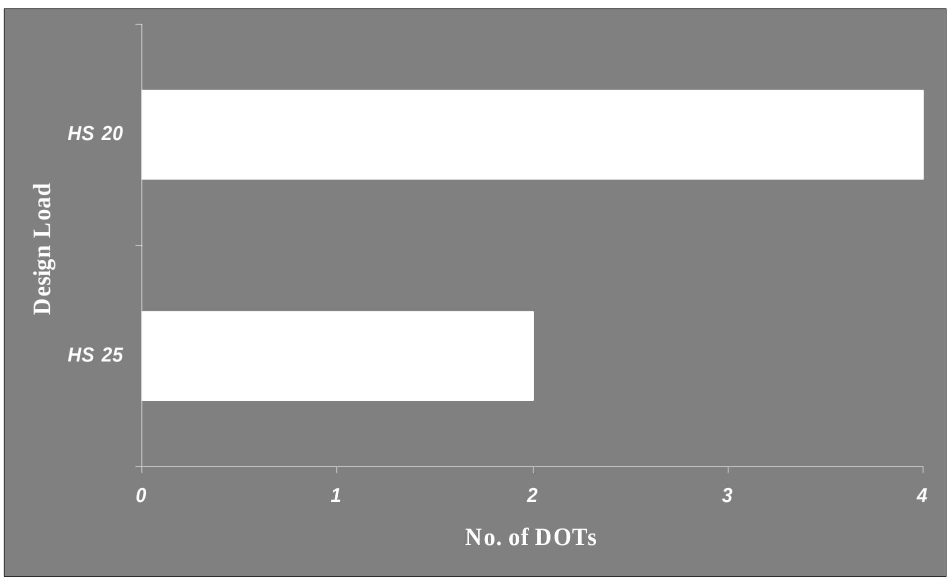


Figure 3-18 Design load

3.1.2.8 Detailed information on completed projects

The following tables illustrate the details with respect to the projects completed by various DOTs.

Table 3-2 FRP bridge deck Projects of Missouri DOT

Project/Bridge Name	Location	Date Installed	Duration (Day)	Manufacturer (Supplier)	# of spans	Size of FPR bridge deck panels (Feet)		No. of FRP bridge deck panels used per span
						Length of panel	Width of panel	
St. Johns St.	St. James	9/2000	10	KSCI	1	8.86 ft.	12.75 ft.	6 – 4" thick
Jay St.	St. James	9/2000	10	KSCI	1	26.92 ft.	2-4.92 ft., 2-7.83 ft.	4 – 5.5" thick
St. Francis St.	St. James	11/2000	5	KSCI	1	26.25 ft.	6.83 ft.	4 – 22" thick

Table 3-3 FRP bridge deck Projects of New York DOT

Project/ Bridge Name	Location	Date Installed	Duration (Day)	# of person	Hours/ person	Manufacturer (Supplier)	Contractor	# of spans	No. of FRP bridge deck panels used per span	Size of FPR bridge deck panels (Feet)	
										Length of panel	Width of panel
Rte 248/Bennetts Creek	Steuben County	10/98	2	8	16	Hardcore	State Forces	1	2	25	16
Rte 367/ Bentley Creek	Chemung County	10/99	5	6	40	Hardcore	State Forces	1	6	14.5	43
Rte 223/Cayuta Creek	Chemung County	10/00	5	6	40	Hardcore	State Forces	1	6	14.5	43
Rte 418/ Schroon River	Warren County	11/00	5	8	50	Martin Marietta	Reale Construction	1	21	8	25
CR 52/Conesus Lake Outlet	Livingston County	12/01	N/A	N/A	N/A	Hardcore	County Forces	1	2	42	16
S Broad St/Dyke Creek	Alleghany County	10/00	N/A	N/A	N/A	Hardcore Composites	County Forces	2	8	7.75	24
CR 46/E Branch Salmon River	Lewis County	10/01	N/A	N/A	N/A	Martin Marietta	County Forces	1	5	8	26
	Washington County	12/02	N/A	N/A	N/A	Martin Marietta	County Forces	N/A	N/A	N/A	N/A

Table 3-4 FRP bridge deck Project of PENN DOT

Project/ Bridge Name	Location	Date Installed	Duration (Day)	# of person	Hours/ person	Manufacturer (Supplier)	Contractor	# of spans	No. of FRP bridge deck panels used per span	Size of FPR bridge deck panels (Feet)	
										Length of panel	Width of panel
SR1037-570 Dubois Creek	Susayehanns County	12-01	1			Hardcore	Fahs-raston	1	2	22'-3"	16'- 5 1/4
County Bridge II	Bedford County	09-02	1	8	8	Martin Marietta	New Enterprise	2	7	8'	22'
4003-0050-0000	Somerset County	10-06-1998	2	9	8	Creative Pultrusions	Somerset Co. PENNDOT Bridge Crew	1	3	?	?
Boyer Bridge	Butler Co.	10-18-01	1	6	7.5	Martin Marietta (Creative Pultrusion)	PENNDOT Forces	1	?	?	?

Table 3-5 FRP bridge deck Project of Illinois DOT

Project/ Bridge Name	Location	Date Installed	Duration (Day)	# of person	Hours/ person	Manufacturer (Supplier)	# of spans	No. of FRP bridge deck panels used per span	Size of FPR bridge deck panels (Feet)	
									Length of panel	Width of panel
Fayette ST Bridge	City of Jacksonville South Fayette street	06/15/01	1	8	5	Martin Marietta	3	3	10	36

Table 3-6 FRP bridge deck Project of North Carolina DOT

Project/ Bridge Name	Location	Date Installed	Manufacturer (Supplier)	Contractor	# of spans	No. of FRP bridge deck panels used per span	Size of FPR bridge deck panels (Feet)	
							Length of panel	Width of panel
GFRP Br#22	Union County	_9_/___/ 2001	Martin Marietta	NCDOT Bridge Maintenance	4	4	10’	24’

Table 3-7 FRP bridge deck Project of Kansas DOT

Project/ Bridge Name	Location	Date Installed	Manufacturer (Supplier)	Contractor	# of spans	No. of FRP bridge deck panels used per span	Size of FPR bridge deck panels (Feet)	
							Length of panel	Width of panel
No Name Creek *	Russell Co.	11/95	Kansas Structural Composites	Russell Co. Hwy Dept.	1	3	23.25’	9.25’
126-19 K-6895-02 (031) Lightening Cr	Crawford Co.	10/15/99	Kansas Structural Composites	Beachner Construction Co.	1	6	8’	31’
126-19 K-6895-02 (035) Limestone Cr	Crawford Co.	10/15/99	Kansas Structural Composites	Beachner Construction Co.	1	6	8’	31’

Table 3-8 FRP bridge deck Project of Delaware DOT

Project/ Bridge Name	Location	Date Installed	Manufacturer (Supplier)	Contractor	# of spans	No. of FRP bridge deck panels used per span	Size of FPR bridge deck panels (Feet)	
							Length of panel	Width of panel
BR 351	Glasgow	Nov. 98	Hardcore	JJIDM Inc.	1	2	30	15
BR 192	Pick Creek	99	Hardcore	JJIDM Inc.	1	1	42	16.5

Table 3-9 FRP bridge deck Project of Maryland DOT

Project/ Bridge Name	Location	Date Installed	Duration (Day)	# of person	Hours/ person	Manufacturer (Supplier)	Contractor	# of spans	No. of FRP bridge deck panels used per span	Size of FPR bridge deck panels (Feet)	
										Length of panel	Width of panel
MD 24/Deer Creek	Harford Country, MD	6/25/01 – 9/15/01	75day	8	9	Martin Marietta	JJIDM Inc.	1	3	10' and 8'	17'-9 ½" and 13'-8 ½"

Table 3-10 FRP bridge deck Project of Oregon DOT

Project/ Bridge Name	Location	Date Installed	Duration (Day)	# of person	Hours/ person	Manufacturer (Supplier)	Contractor	# of spans	No. of FRP bridge deck panels used per span	Size of FPR bridge deck panels (Feet)	
										Length of panel	Width of panel
Lewis & Clark Bridge	Astoria, Clastsop Co., OR	2001	15	5 – 6 Max.		Martin Marietta	Hamilton Constr.	1	12 for L = 113'- 8"	Typ. 10'	± 20' (full bridge)
Old Youngs Bay Bridges	Astoria, Clastsop Co., OR	2002	22	5 – 6 Max.	8	Martin Marietta	Hamilton Constr.	1	17 for L = 166'	Typ. 10'	± 21' (full bridge)

3.1.2.9 Barriers encountered in installing FRP bride deck panels

Except for two DOTs (*North Carolina and Oregon DOT*) all other respondents currently using FRP bridge deck panels, experienced at least one barrier during installation of the panels. Especially, the design and construction barrier was listed among the top barriers by 5 DOTs and vendor barrier was listed as being limited to only one or two suppliers.

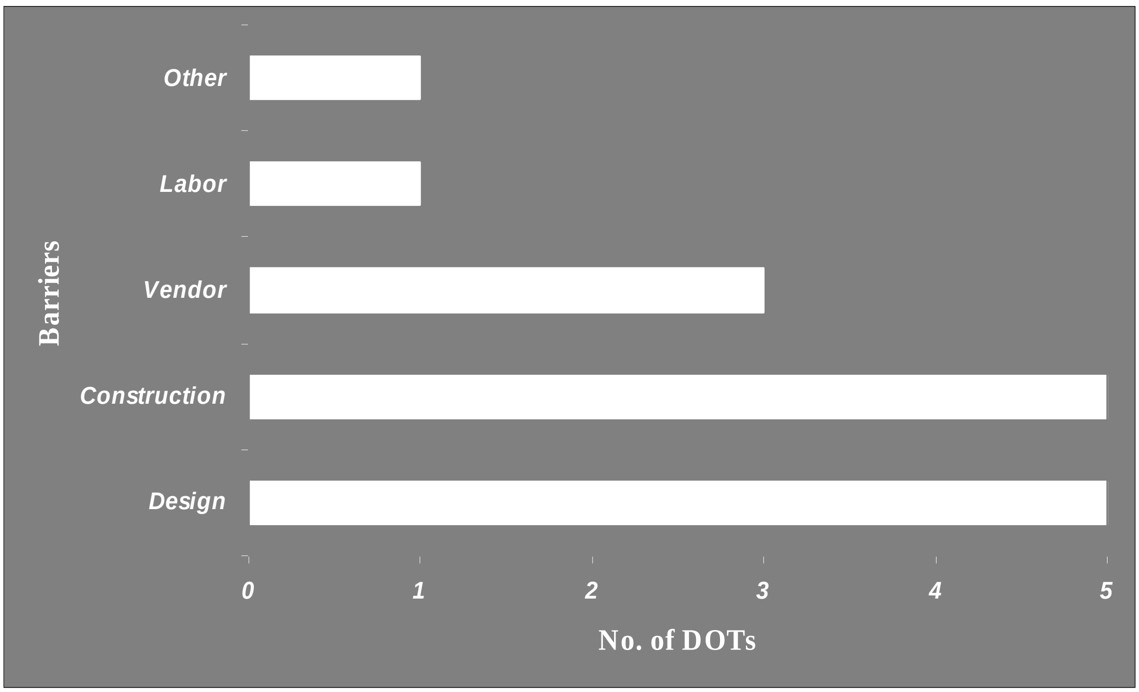


Figure 3-19 Barriers encountered in stalling FRP bride deck panels

The following is a summary of barriers encountered in installing FRP bridge deck panels:

- ❑ Design barriers:
    - o Lack of specifications
    - o Must rely on manufacturer design

- Parapet connection (No design specification for all bridges)
- New concepts for connections
- Unknown design parameters

- Construction barriers:
  - Contractor Unfamiliarity
  - Lack of knowledge of system
  - Too much field modification without design review
  - Unknown installation and handling methods
  - Tolerance issues that lead to saw cuts having to be made. The tolerance issues were due to fabrication and panel connection tolerances. Due to these tolerances, the panels ended up being slightly longer than anticipated. When the last panel was set, it overhung the bridge by a few inches. To correct this and allow the panel to fit, the extra was cut off and the panels were inserted without any further problems.
- Labor barriers:
  - Unskilled labor
- Vendor barriers
  - Only one FRP manufacturer bid for the job
  - Limited to Kansas Fabricator
- Other barriers:
  - Who is responsible for girder/panel connection

3.1.2.10 Delivery issues

It is one of the important issues to reduce construction duration. With regard to delivery issues, three questions were asked: (i) the method of delivery of FRP bride deck panels, (ii) the maximum size of FRP bridge deck panels transported and the cost of transportation, and (iii) the required delivery time. All respondents indicated that a Flat-bed truck was used to deliver the panels from the factory to the job site. Their maximum size was a variable depending on the project requirements. The summary of the responses with respect to the panel size is as follows:

- 14.5’ x 43’
- 9’ x 40’
- 22’3’’x 16’5.25”
- 8’ x 22’
- 8’ x 25’6.5”
- 30’x 15’
- 10’ x 17’9.5”
- 10’ x 20’

As for the delivery time, if the fabrication facility was located near a particular project and the FRP bridge deck panels were fabricated ahead of time, they could be shipped by the flat bed truck when they were needed. Therefore, in this particular case, it took a few hours to deliver them to the project site (i.e., 1.5 to 3 hours). However, otherwise, it took about one week. A few days were usually required to deliver the panels (i.e., 1 or 2 days)

3.1.3 Maintainability and Operability issues of FRP bridge deck panels

Respondents were asked about the condition rate of the bridge decks and substructure when FRP bridge deck panels were considered for replacing deteriorated bridge decks. As shown in Figure 3-20, the deteriorated bridge decks were mostly replaced when their CR was 4 and whereas CR of 6 or 7 was considered for the deteriorated bridge substructures. Most of the DOTs use a scale of 0-9 (0: Failed Condition- 9: Excellent Condition) to measure the condition rate. Whereas, New York uses a scale from 0-7 (0: Failed Condition- 7: Excellent Condition) for the measurement of condition rate (CR) of bridge structures. For New York DOT, the bridge decks and substructure are replaced when their CR is 4 and 3 respectively.

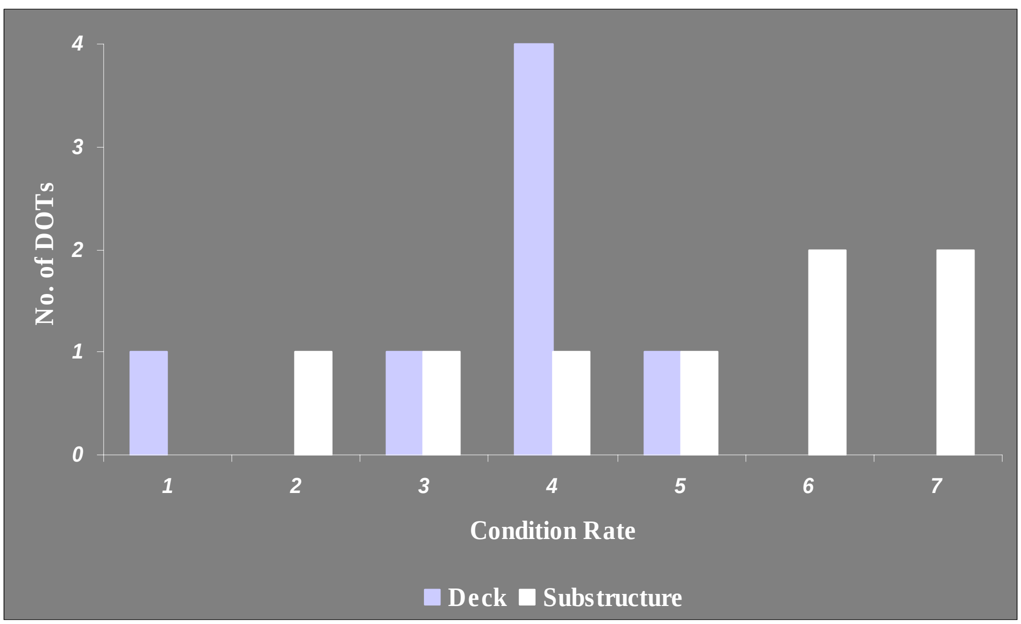


Figure 3-20 Condition rating of existing bridge structures

Since the FRP bridge deck panels have been applied for highway bridge structures over the last few decades, most of the DOTs currently using them do not have a lot of experience in their maintenance. Therefore, it is impossible to collect their performance data including maintenance records which is one of obstacles in the application of new material in construction area. Therefore, this research identified various issues or problem with regards to maintenances and operation after they were installed. Based on the results of the questionnaire survey, Delaware, Maryland, and North Carolina DOTs have not experienced any maintenance problems. The following is a summary of other DOTs with regard to maintenance and operability issues.

- New York DOT: Durability of wearing surface. On three bridges there has been delamination of the polymer concrete wearing surface from the FRP deck. It has since been corrected by better surface preparation of the FRP deck (Sandblasting). Also there has been some localized delamination in the deck between the skin and the core. This can be repaired by epoxy injection.
- Ohio DOT:
    - Delamination and unbonded areas in panel skins
    - Deck-to-girder connection at haunches
    - Field and shop joint problems
    - Polymer wearing surface deficiencies
    - Cracks in concrete wearing surface
    - Joints between different deck systems
    - Water intrusions
    - Existing fire damage
- Kansas DOT
    - Field modifications of connection to girders

- Deck surface problems (wearing surface)

- Oregon DOT:
  - Wearing surface problem
- Pennsylvania DOT
  - Epoxy overlay delamination

Except for Delaware, 8 DOTs don't have specific analysis procedure or method established in order to inspect, maintain, and repair the FRP bridge deck panels. In Delaware DOT, Sensors and gauges are installed for regular inspection. In terms of inspection and monitoring the service of FRP bridge deck panels, biannual inspection has been performed by Maryland and Oregon DOT.

In case of Pennsylvania DOT, the first and second projects have been monitored for 3 years and load test was performed for all four projects. Especially, the fourth project has been monitored as part of FHWA IBRC contract to determine composite action between steel stringer and FRP panels (refer to Table 3-4)

Table 3-11 Expected service life of Concrete versus FRP bridge deck panels

DOT	Average service life of Concrete Bridge Deck (Year)	Expected service life of FRP Composite Bridge Deck (Year)
New York	25	75
Ohio	30	75
Pennsylvania	40:Epoxy coated rebar 30: Black rebar	40-75
Illinois	25	Unknown
Kansas	30	Unknown, maybe 10 to 20 years
Delaware	Unknown	75
Maryland	50	Over 100
Oregon	15	75

Respondents were also asked what the expected service life of FRP bride deck panels was as compared to average service life of concrete bridge decks. A total of 8 DOTs responded to the question and the responses are summarized in Table 3-11.

3.1.4. Construction cost of FRP bridge deck panels

DOT	Initial construction cost
New York	$ 65 -75/SF
Pennsylvania	(1) SR1037-570 Dubois Creek - Initial construction: Unit cost: 465/sf, total:341,500 (2) County Bridge II - Initial construction cost: 485,000 (lump sum bid) - Engineering and fabrication cost 60,000 - testing -171,000 (3) 4003-0050-0000 - Initial construction cost: 125,000 (material only) - Engineering and fabrication cost: 39,000 -Maintenance cost: 25,000 (4) Boyer Bridge -Initial construction cost: 129.60/sf Total:138,802.77
Delaware	(1) BR 351 Project - Initial construction cost : 220,000 (244.44/sf) - Engineering and Fabrication cost: 760,000 (844.44/sf) (2) BR 192 Project: - Initial construction cost = 250,000 (360.75/sf)
Maryland	Initial construction Cost: $911,057.70 Engineering and Fabrication Cost: ≈ $ 91,108

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CHAPTER 4: PRELIMINARY DATA COLLECTION AND DATA ANALYSIS (CASE STUDY AND INTERVIEWS)

4.1 Introduction

In addition to the questionnaire survey, case studies and interviews were conducted to collect preliminary data on constructability, operability, and maintainability of FRP bridge deck panels. This chapter illustrates the results of the case studies and interviews. Seven candidate projects were selected for the case studies. Five out of seven candidate projects (Sintz Road over Rock Run Bridge in Clark County, Five mile Road Bridge #0171, 0087, and 0071 in Hamilton County, and Westbrook Road Bridges in Montgomery County) were under Project 100 in Ohio and two candidate projects (Fairgrounds Road Bridges in Greene County and County Line Road over Tiffin River in Defiance County) were part of a new program called 'Composites For Infrastructure' (C4I). The county engineers of the candidate projects were interviewed during the case studies. This chapter elaborates upon the finding of the case studies and interviews including detailed information about C4I and Project 100 in Ohio. In order to collect additional data on constructability, operability, and maintainability of FRP bridge deck panels from a manufacturer point of view, the research team visited two manufacturing facilities, Hardcore Composites Inc. (HCI), and Martin Marietta Composites (MMC). This chapter also elaborates upon the results of interviews with their engineers.

4.2. Project 100 in Ohio

4.2.1 Project 100

'Project 100'was initiated by the state of Ohio to encourage and enhance commercial growth of FRP composites bridge decks. The main objective of this program was to design, manufacture and install a composites bridge decks in each of Ohio's 88 counties and 12 Department of Transportation districts between 2000-2005 (Reeve 2000). Another goal of 'Project 100' was economic development in Ohio by establishing an industry that would develop and supply composite bridge decks to the eastern United States (Project 2003)

Under this program, the Ohio Department of Development (ODOD) assisted the counties and districts by subsidizing the high initial installation cost of FRP bridge decks. The National Composites Center (NCC) helped counties and districts in selecting a project and working with FRP deck manufacturers as well as the Ohio Department of Transportation (ODOT).

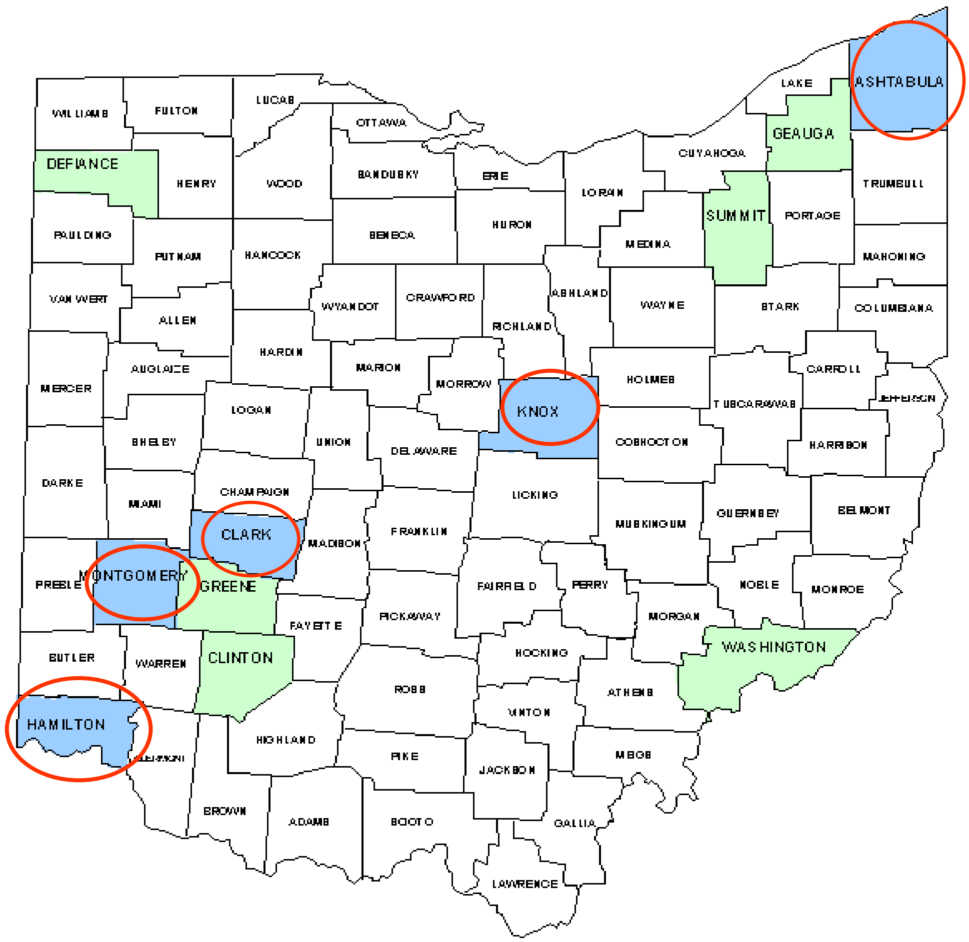


Figure 4- 1 FRP Composites Decks installed in Project 100

- During Phase-I of Project 100 (Project
  - ❑ NCC selected Hardcore Composites of New Castle, Delaware to supply the deck panels.
  - ❑ Hardcore Composites agreed to invest in local facilities to manufacture the panels, thereby creating a new industry in Ohio (Project 2003 and Reeve 2000).
- Composite decks installed under Project 100 by the end of Phase I
  - ❑ Ashtabula County: Shaffer Road Bridge

- Clark County: Sintz Road over Rock Run Bridge
- Hamilton County: Five mile Road Bridge # 0171, 0087, and 0071 bridges
- Knox County: Elliot Run Bridge
- Montgomery County: Spaulding Road and Westbrook Road bridges
- Wright Patterson AFB: Hebble Creek bridges

- Two conditions were required to accomplish the Project 100
  - A single supplier would have to be "guaranteed" a significant share of the market to justify investment in an Ohio plant
  - State funding would be required to subsidize bridge owners for more costly FRP decks in the near term until costs were reduced to a point at which FRP decks became competitive with conventional materials (Project 2003 and Reeve 2000)

During the first 18 months of the project 100, the two conditions were satisfied, however, the two conditions were not satisfied for the full planned duration of the project 100. The lack of state funding for Phase II of Project 100 lead NCC to redefine the program since the Ohio biennial budget for FY 2002 – 2003 did not include funds for Phase II of Project 100. Another factor forcing the program was procurement regulations, which make it impossible to direct a sufficiently high enough volume of business to a specific supplier (Hardcore Composites) to set up an adequate economic presence in Ohio. Therefore, NCC took into account other ways to achieve the economic development objective of the program (Project 2003 and Reeve 2000).

4.2.2 Composites for Infrastructure (C4I) Initiative

Under a new program called Composites for Infrastructure (C4I), NCC signed an agreement with MMC in Aug. 2001. The initiative focuses on facilitating FRP bridge deck installations without state subsidy and examining other infrastructure related applications for composite materials. Under the C4I, the first composite bridge deck was Greene County Fairgrounds Road and the largest to date to be successfully installed

- Composite decks installed under C4I initiative
    - Greene County: Fairgrounds road bridge
    - Summit County: Hudson road/wolf creek Bridge
    - Geauga County: Hotchkiss road bridge
    - Washington County: Cats creek bridge
    - Clinton County: Hales branch road bridges
    - Defiance County: County line road over Tiffin River

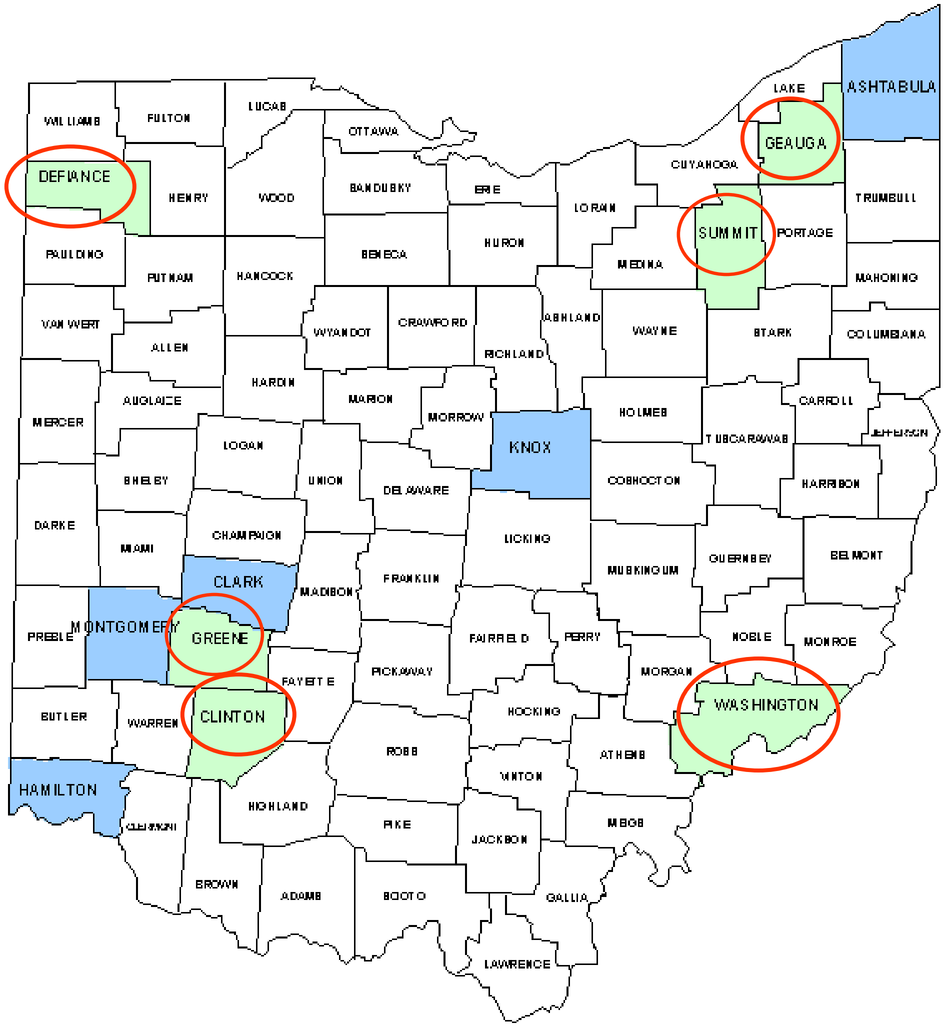


Figure 4-2 Composite decks installed under C4I initiative

4.3 Case Studies about FRP bridge deck construction

Five counties in Ohio were visited by the research team to collect data on constructability, maintainability, and operability of FRP bridge deck panels. In addition to the interview with county engineers, questionnaire survey was used to establish state of practice of fabrication and use of composite bridge decks. This section illustrates the data obtained from four out of five counties (except for Montgomery County).

4.3.1 General Information and Interview Results

CASE STUDY-1: Sintz Road over Rock Run Bridge, Clark County

Personnel Interviewed: Bruce Smith, County Engineer

Doug Frank, County Bridge Superintendent

Paul W. Debuty, Bridge Designer

- ,Clark County does not have any plans within next 5 years for installation of new FRP bridge deck panels
- Unlike some other counties, Sintz Road over Rock Run Bridge located in Clark County used 50 Z clips instead of a haunch.
- The ADT of the bridge was 1600 (10% truck) - *Low volume rural.*
- The project was the third out of Project 100.
- County engineers were mostly not satisfied by the work done by Hardcore Composites because they did not provide any technical help at the job site for installation.
- The speed limit for the bridge is 55 MPH.
- On time delivery and better quality control of decks was considered as an important issue for future projects utilizing FRP bridge deck panels.
- The criteria used for selecting a bridge for FRP bridge deck panel application included:
    - Low ADT, No skew, No Super-elevation, Low ADTT.
- Any preference in the supplier of FRP bridge deck panels

- The first and only bridge was supplied by Hardcore Composites. But the county would likely use another supplier due to the poor quality of the panels on future projects.

CASE STUDY-2: County line road over Tiffin River, Clark County

Personnel Interviewed: Warren Schlatter, Chief Deputy Engineers.

- Within 5 years, a new project has been scheduled for installation of FRP bridge deck panels
- The FRP composite bridge deck panels were used in ***High volume rural.***

CASE STUDY-3: Fairgrounds road bridge, Greene County

Personnel Interviewed: Bob Geyer, County Engineer

- No new bridge deck panels have not been scheduled for installation in the near future (within 5 years)
- The FRP composite bridge deck panels were used in ***High volume rural.***
- 15,200 car traffic volumes in a day is not heavy traffic for this bridge.
- The reason for selecting Martin Marietta:
    - Warranty from Martin Marietta Composite: 30 years for their material
    - Recommendation by consultant
- The criteria of your state for selecting a bridge for FRP bridge deck panel application
    - Need a grant for the construction because of high initial cost.
- The project started in March 2001 and finished on June 2, 2002.
- Miscalculated amount of grout that lead to change order.

- Contractor: AHERN associate, in Springfield, OH
- Engineer: LJB, in Dayton. (Mark Handerson)
- NCC is supposed to monitor the bridge but they are not sure whether NCC is doing or not because they have not seen any results.
- 3 spans, 2 abutments, and 2 piers
- Problem issues: keeping tolerance around deck edge with guardrail straight
- The price of the whole project is twice as compared to a conventional project.
- One of the future concerns is that if the epoxy is delaminated from the deck, how to get the deck off, how to get the fiber glass for replacement, and how to patch it back in place.
- In terms of monitoring system
    - Dead load and temperature is always monitored, also visual inspection of under and over the surface is done by NCC. They check the color of the surface and any change of color brings attention.
    - Live Load Tests: Conducted every six months for Greene County FRP deck for 2 years and data on load transfer and deflection is collected.
    - Continuous monitoring of temperature: data is collected continuously and analyzed every month
    - Monitor: Temperature effects, Shear load transfer at field joints, Shear load transfer at deck-to-girder connection, and Deflection
    - Monitoring for Greene and Clinton Counties was funded by Innovative Bridge Research and Construction (IBRC) program

CASE STUDY-4: Five Mile Road Bridge # 0071, # 0087, and #0171, Hamilton County

Personnel Interviewed: Steve Mary, County Engineer

- No new bridge deck panels have been scheduled for installation in the near future (within 5 years)
- The criteria for selecting a bridge for application of FRP bridge deck panels
    - Existing substructure in good shape and existing concrete beam in good shape.
- The first bridge took 2 and half day to set up the FRP bridge deck panel and one day for second and third bridge. There is a learning curve. However, it took two years to finish the three projects (Five mile road bridge # 0171, 0087, and 0071) because a lot of time was required for pre-engineering including the selection of FRP deck manufacturer.
- Project engineer: LJB, in Dayton. (Mark Handerson)
- Contractor: Forth Defiance County (No choice in selecting contractor)
- One year warranty on material from Hardcore Composites
- There was no competitive bid in the selection of supplier for the FRP bridge deck panels

CASE STUDY-5: Salem Avenue Bridge, Westbrook Road Bridge over Dry Run Creek, and Spaulding Road Bridge, Montgomery County

Personnel Interviewed: Roberts S. Hoag, Chief Deputy Engineer

A. Salem Avenue Bridge

Figure 4-3 Salem Avenue Bridge

- A five span continuous haunched steel plate girder structure
- Six lanes of traffic over the Great Miami River on SR 49 in Dayton, Ohio.
- Consisted of six girders spaced at about 8 feet 9 inches.
- Ohio Department of Transportation (ODOT) decided on an innovative replacement strategy
    - Replace the concrete bridge deck of this bridge
    - Develop added field experience to support the transportation industry's ongoing search.
    - Used four different FRP composite deck systems
        - Composite Deck Solution (CDS), Dayton, Ohio
        - Creative Pultrusions, Inc. (CPI), Alum Bank, Pennsylvania
        - Hardcore Composites, Inc. (HCI), Newcastle, Delaware
        - Infrastructure Composites, Inc. (ICI), San Diego, California

- o 80% funds provided by the Federal Highway Administration (FHWA) and 20% by ODOT

- Contractor: National Engineering, Cleveland, Ohio
- Wearing surface: Poly-Carb, Inc., Cleveland Ohio
- Montgomery County engineers have responsibility on long-term maintenance.
- Maintenance problems identified by the evaluation team
  - o Delamination and unbonded areas in panel skins

Figure 4-4 Debonding of the wearing surface

  - o Deck-to girder connection at haunches: Some of the CPI, HCI, and ICI panels were observed to be lifted off the haunch as much as 1/16 inch.
  - o Field and shop joint problems

Figure 4- 5 Wearing surface cracking at a deck joint

- Polymer wearing surface deficiencies
- Cracks in concrete wearing surface

Figure 4-6 Concrete Cracks in CDS deck system

- Joints between different deck systems
- Water intrusion: Water was found within the HCI panel
- Existing fire damage: fire damage was found alongside an in-service HCI deck panel (Panel No. 7). No obvious structural damage occurred.

B. Westbrook Road Bridge over Dry Run Creek

Figure 4-7 Westbrook Road Bridge over Dry Run Creek

- Deck Dimensions: 34 feet 3 inch * 32 feet 8 inch
- Total square footage: 975
- Design load: HS 20
- Single span
- Wearing surface: asphalt
- Guardrail attached to deck
- Manufacturer and manufacturing method: HCI and VARTM

C. Spaulding Road Bridge

- Deck Dimensions: 83 feet 1 inch * 56 feet
- Total square footage: 4,653
- Design load: HS 20

- Single span
- Wearing surface: asphalt
- Guardrail: Concrete
- Manufacturer and manufacturing method: HCI and VARTM

4.3.2 Clark County, OH

Figure 4-8 Sintz Road over Rock Run Bridge

- Project or bridge name: CLA-TR-231
- Location: Sintz Road
- Date installed: October 2000
- Project Duration(Day): About 60
- Number of person: About 4

- Hours/person: 8
- Deck dimension: 62 feet * 30 feet
- Total square footage: 1,860
- Manufacturer: HCI
- Contractor: Pitoenix bridge
- Number of span: 1
- Number of FRP bridge deck panels used per span: 6
- Size of FRP bridge deck panels: 30 feet long and 10 feet wide

4.3.2.1 Construability issues of FRP bridge deck panels

- *Wood or Timber* among deck structure types has been replaced by FRP bridge deck panels.
- *Epoxy adhesive* is employed for the connection of FRP bridge deck panels. ('Glued' with a product called 'Plexus')
- Method employed for the connection between the FRP bridge deck panels and girder or stringer: Steel S-Clips attached to studs along bottom of panels

Figure 4-9 Steel S-Clip attached to studs along bottom of panels

- Use of Z clips instead of grout haunch

Figure 4-10 Z clips

- *Bituminous* (over waterproofing) is used as the material of the wearing surface applied for FRP bridge deck panels.
- Wearing surface aggregate: ODOT specification 404, asphalt concrete

Figure 4- 11 Sample of wearing surface used in Sintz Road over Rock Run Bridge

- Manufacturing process: Closed Molding (Vacuum Assisted Resin Transfer Molding: VARTM)
- No construction specification of FRP bridge deck panels
    - No warranty issues and experimental Features
- Design Load and deflection limitation: HS-20
- Guardrail is connected to the outside beam connection between panels

Figure 4-12 Guardrail cantilevered from girders

- Barriers
    - Construction barriers: FRP panel dimensions varied
    - Vendor barrier: Epoxy machine was not working correctly.
- The cross-section type
    - Hardcore composites: Sandwiched panel
- Flatbed Truck is used for delivery of FRP bridge deck panels from factory to job site.
- The maximum size of FRP bridge deck panels transported: N/A
- Delivery time of FRP bridge deck panels from factory to job site: N/A

<u>4.3.2.2 Maintainability and Operability issues of FRP bridge deck panels</u>

- When the condition rate of bridge decks was 4, FRP bridge deck panels were considered for replacing deteriorated bridge decks.
- When the condition rate of the substructure was 3, FRP bridge deck panels were selected.
- Specific analysis procedure or method established in order to inspect, maintain, and repair the FRP bridge deck panels
    - Visual inspection 3-4 times per years. Any repairs to the panels will be based on discussion with the manufacturer.
- In terms of inspection and monitoring the service of FRP bridge deck panels
    - Tap test is performed every year.
- Issues/problems with maintenance and operation after the FRP bridge deck panels were installed: No.

Figure 4-13 Fire damage found in the bottom of panels

- Average service life of Concrete Bridge Deck: 25-30 years
- Expected service life of FRP Composite Bridge Deck: 50-100 years

4.3.2.3 Construction cost of FRP bridge deck panels

- Initial Construction Cost: $91.40/sf
- Engineering Cost: $ 21.51/sf

4.3.3 Defiance County, OH

Figure 4-14 County line road over Tiffin River

- Project or bridge name: CR1-Defiance/Wil County Line
- Date installed: July 2003
- Deck dimension: 186 feet 6 inches * 28 feet
- Total square footage: 5,222
- Manufacturer: MMC
- Number of span: 3
- Number of FRP bridge deck panels used per span: 8
- Size of FRP bridge deck panels: 8 feet long and 28 feet wide

4.3.3.1 Construability issues of FRP bridge deck panels

- *Concrete Cast-in-place* deck structure was replaced by FRP bridge deck panels.

- *Epoxy adhesive* and *Tongue and groove ends* are employed for the connection of FRP bridge deck panels.
- Grouted studs are employed for the connection between the FRP bridge deck panels and girder or stringer
- *Bituminous* is used as the material of the wearing surface applied for FRP bridge deck panels.
- Wearing surface aggregate: N/A
- The manufacturer for wearing surface: N/A
- Manufacturing process: Closed Molding (Pultrusion) : Deck thickness = 8 in

Figure 4-15 Sample of FRP bridge deck panels (Manufacturer: MMC)

- No construction specification of FRP bridge deck panels (Job Specific specifications have been used)
- Warranty from Manufacturer: N/A
- Design Load: HS25
- Deflection limitation: N/A
- Guardrail is connected to the outside beam connection between panels

Figure 4-16 Guardrail cantilevered from girders

- Barriers: Design barriers (Manufacturer insisted on using shear studs as connection detail)
- The cross-section type
    - Martin-Marietta
- Flatbed Truck is used for delivery of FRP bridge deck panels from factory to job site.
- The maximum size of FRP bridge deck panels transported: N/A
- Delivery time of FRP bridge deck panels from factory to job site: N/A

4.3.3.2 Maintainability and Operability issues of FRP bridge deck panels

- When the condition rate of bridge decks was 2, FRP bridge deck panels were considered for replacing the deteriorated bridge decks.

- When the condition rate of the substructure was 7, FRP bridge deck panels were selected.
- No specific analysis procedure or method established in order to inspect, maintain, and repair the FRP bridge deck panels.
- Average service life of Concrete Bridge Deck: 30 years
- Expected service life of FRP Composite Bridge Deck: 75 years

4.3.3.3 Construction cost of FRP bridge deck panels

- Initial Construction Cost: $93/SF

4.3.4 Greene County, OH

Figure 4- 17 Fairgrounds road bridge

- Project or bridge name: Fairgrounds Road Bridge

- Date installed: May 2002
- Duration of Installation (Day): 3
- Number of person: 10
- Hours/person: 10
- Deck dimension: 227 feet * 32 feet 6 inches
- Total square footage: 7,400
- Manufacturer: MMC
- Contractor: AHERN associate
- Number of span: 3
- Total number of FRP bridge deck panels used: 28
- Size of FRP bridge deck panels: 32 feet long and 8 feet wide

4.3.4.1 Construability issues of FRP bridge deck panels

- *Concrete Cast-in-place* deck structure types was replaced by FRP bridge deck panels.
- *Epoxy adhesive* is employed for the connection of FRP bridge deck panels.
    - Panels were connected by epoxy and attached to beams with shear studs and grout
- Method employed for the connection between the FRP bridge deck panels and girder or stringer
    - Shear studs and grout in pockets
- *Polymer modified asphalt* is used as the material of the wearing surface applied for FRP bridge deck panels.
- Wearing surface aggregate: Natural aggregate

- The manufacturer for wearing surface: Barrett paving materials
- Manufacturing process: Closed Molding (Pultrusion) : deck thickness = 8 in
- No construction specification of FRP bridge deck panels (Job Specific specifications have been used)
- Warranty from Manufacturer: 30 years
- Design Load: HS40
- Deflection limitation: N/A
- Barriers: Cost
- The cross-section type
    - Martin-Marietta
- Flatbed Truck is used for delivery of FRP bridge deck panels from factory to job site.
- The maximum size of FRP bridge deck panels transported: 32’ * 8’
- Guardrail is attached to FRP bridge deck
- Delivery time of FRP bridge deck panels from factory to job site: 1 Day

Figure 4-18 Guardrail attached to deck

4.3.4.2 Maintainability and Operability issues of FRP bridge deck panels

- When the condition rate of bridge decks was 4, FRP bridge deck panels were considered for replacing deteriorated bridge decks.
- When the condition rate of the substructure was 6, FRP bridge deck panels were selected.
- No specific analysis procedure or method established in order to inspect, maintain, and repair the FRP bridge deck panels.
- Issues/problems with maintenance and operation
    - Delamination, debonding, and cracking of wearing surface
    - Keeping tolerance around deck edge with guardrail straight
    - Some minor gaps between FRP deck bottom and concrete beams

Figure 4-19 De-bonding, and cracking of Wearing surface

Figure 4- 20 Keeping tolerance around deck edge with guardrail straight

- Average service life of Concrete Bridge Deck: 50 years
- Expected service life of FRP Composite Bridge Deck: N/A

4.3.4.3 Construction cost of FRP bridge deck panels

- Initial Construction Cost: $90/SF
- Total Cost: $675,000

4.3.5 Hamilton County, OH

Figure 4-21 Five Mile Road Bridge # 0171

Figure 4-22 Five Mile Road Bridge #0087

	Five Mile Road Bridge # 0071	Five Mile Road Bridge # 0087	Five Mile Road Bridge #0171
Location	Five Mile Road	Five Mile Road	Five Mile Road
Date installed	November 30. 2001	May 26. 2001	November 30. 2000
Duration (day)	1	1	1
Number of person	5 – 6	5 – 6	5 – 6
Hours/person	8	8	8
Manufacturer	HCI	HCI	HCI
Contractor	Ft. defiance Constr.	Ft. defiance Constr.	Ft. defiance Constr.
Number of spans	1	1	1
No. of FRP bridge deck panels used per span	±6	±6	±6
Size of FRP bridge deck panels (Feet)	Length: 30 feet Width: Various	Length: 30 feet Width: Various	Length: 30 feet Width: Various
Deck dimension	44 feet * 28 feet	47 feet * 30 feet	44 feet * 28 feet

4.3.5.1 Construability issues of FRP bridge deck panels

- *Concrete Cast-in-place* deck structure types was replaced by FRP bridge deck panels.
- *Epoxy adhesive* and *Tongue-and-groove ends* are employed for the connection of FRP bridge deck panels. ('Glued' with a product called 'Plexus')
- Method employed for the connection between the FRP bridge deck panels and girder or stringer (Refer to the picture below):

- Nelson Stud: It is a steel bar about 7/8" in diameter that is welded to the plate on the top of the beam through a hole that was fabricated in the deck. There is a Nelson Stud gun that does this very quickly as compared to normal welding procedures.
- Mechanically bolted to concrete I-beams
- Void between FRP and concrete flange filled with grout.

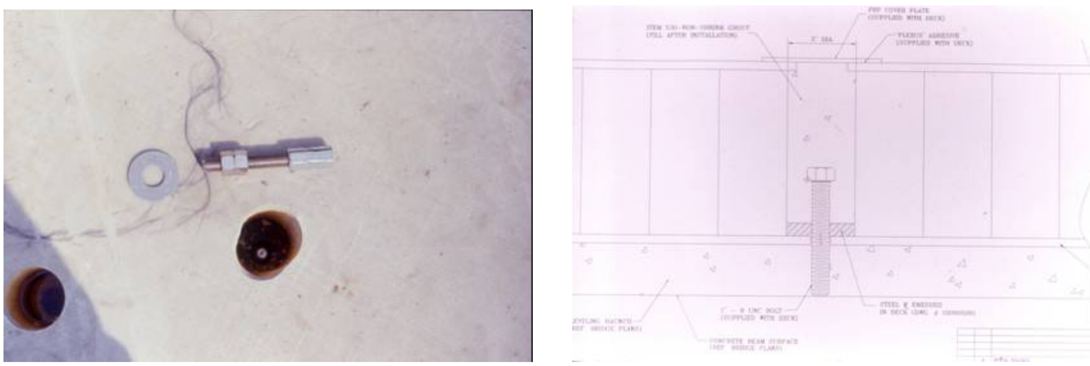


Figure 4-23 Nelson Stud method

- *Bituminous* (over waterproofing) is used as the material of the wearing surface applied for FRP bridge deck panels.
- Wearing surface aggregate: Coarse + Fine Aggregate in asphalt
- Guard Rail: Attached to deck

Figure 4- 24 Guardrail attached to deck

- A manufacturer for wearing surface: N/A, Local plant
- Manufacturing process: Closed Molding (Vacuum Assisted Resin Transfer Molding)
- No construction specification of FRP bridge deck panels (Job Specific specifications have been used)
- No warranty and No experimental Features
- Design Load and deflection limitation: N/A
- Barriers: Design barriers (Guardrail), Vendor barriers (Located in Delaware)
    - Other problem: It was tough to get enough **'Plexus'** material in tongue and groove areas before it began to set up.
- The cross-section type
    - Hardcore composites: Sandwiched panel

Figure 4-25 Honeycomb cells of sandwiched panels

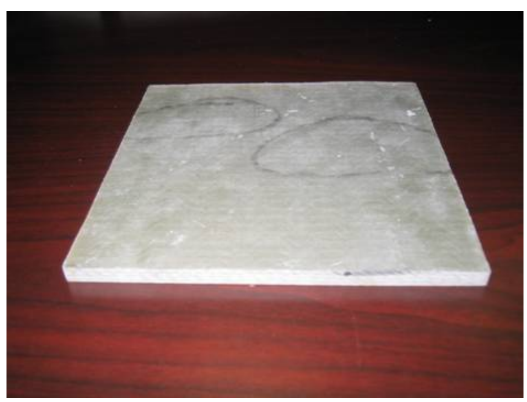


Figure 4-26 Face sheets of sandwiched panels

- How does beam spacing affect the slab thickness in FRP bridge deck panels?
    - Needed an 8" panel due to existing beam spacing

- Flatbed Truck is used for delivery of FRP bridge deck panels from factory to job site.
- The maximum size of FRP bridge deck panels transported: N/A
- Delivery time of FRP bridge deck panels from factory to job site: N/A

4.3.5.2 Maintainability issues of FRP bridge deck panels

- When the condition rate of bridge decks was 3, FRP bridge deck panels were considered for replacing deteriorated bridge decks.
- When the condition rate of the substructure was 7, FRP bridge deck panels were selected.
- No specific analysis procedure or method established in order to inspect, maintain, and repair the FRP bridge deck panels.
- Visual inspection has been performed every one year after FRP bridge deck panels were set up.
- Issues/problems with maintenance and operation after the FRP bridge deck panels were installed:
    - Some shims on one deck
    - There were some minor gaps between FRP deck bottom and concrete beams
- Average service life of Concrete Bridge Deck: 50 years
- Expected service life of FRP Composite Bridge Deck: 100 years

4.3.5.3 Operability issues of FRP bridge deck panels

(1) B-0071: FRP deck – material + installation: $ 75/SF,
Total cost: 100,500.00

(2) B-0087: FRP deck – material + installation: $ 75/SF
Total cost: 105,825.00

(3) B-0171: FRP deck – material + installation: $ 75/SF
Total cost: 98,325.00

4.4 Result analysis of questionnaire survey

The following issues on FRP bridge deck panels are analyzed according to the response to the questionnaire survey from four counties (except Montgomery County).

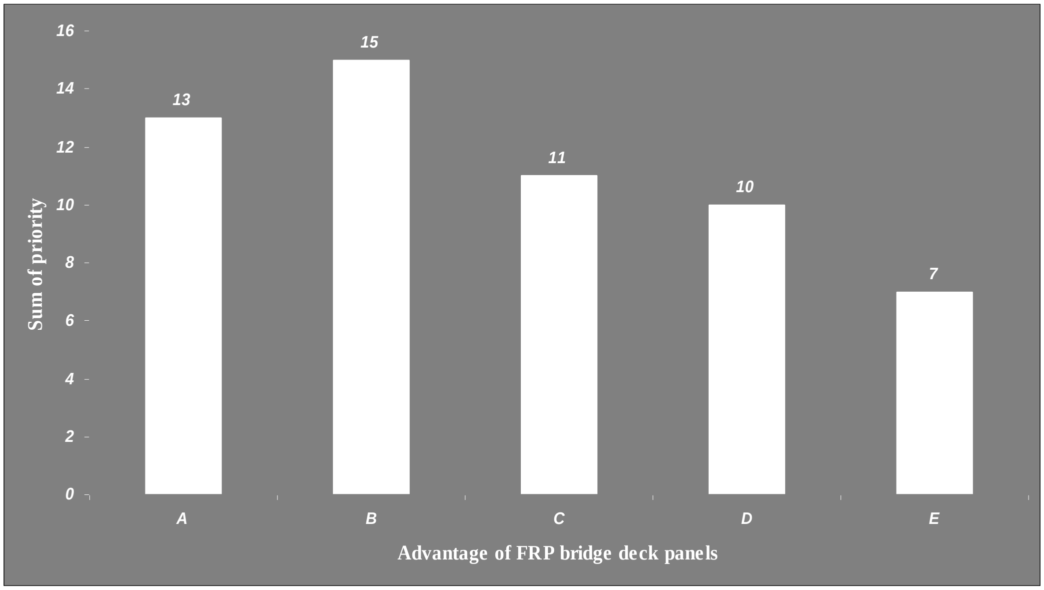


Figure 4-27 Advantage of FRP bridge deck panels

(1) Advantage of FRP bridge deck panels

The county engineers were asked to list the advantages of FRP bridge deck panels using a scale of 1-5 where (1 = least priority and 5 = top priority). Four county engineers except for Montgomery County engineers answered the question. A-E of horizontal axis in Figure 4-7 represents the advantage of FRP bridge deck panels: **A**. Increased capacity for live load with possible elimination of weight restrictions, **B**. Good durability, fatigue resistance, long service life, resistance to de-icing salts, **C**. Fast installation due to modular, prefabricated nature, and reduced traffic delay, **D**. Cost saving, less expense for maintenance than total replacement, and **E**. Less environmental impact and fewer permits required than replacement.

The opinion of county engineers are same as that of bridge engineers mentioned in Chapter 3 in that they were skeptical that FRP composites bridge decks have less environmental impact and require few permits as compared to conventional decks. Similarly, county engineers somewhat doubted that FRP bridge deck panels could offer cost saving, less expense for maintenance than total replacement.

(2) Road type of application for FRP bridge deck

In low volume rural, four deteriorated conventional bridge decks have been replaced by FRP bridge deck panels. In high volume rural, FRP bridge deck panels were used to replace two deteriorated conventional bridge decks. It is important to note that while the FRP bridge deck panels made by HCI were used in low volume rural, those made by MMC was all used in high volume rural (Refer to Figure 4-28)

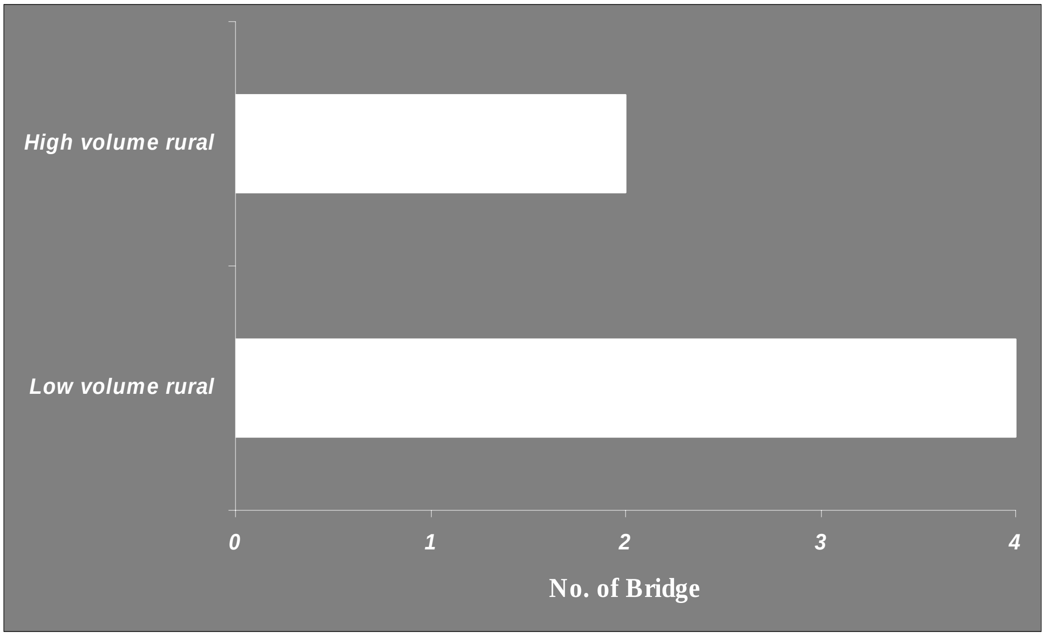


Figure 4-28 Road type of application for FRP bridge deck panels

(2) Deck structure type

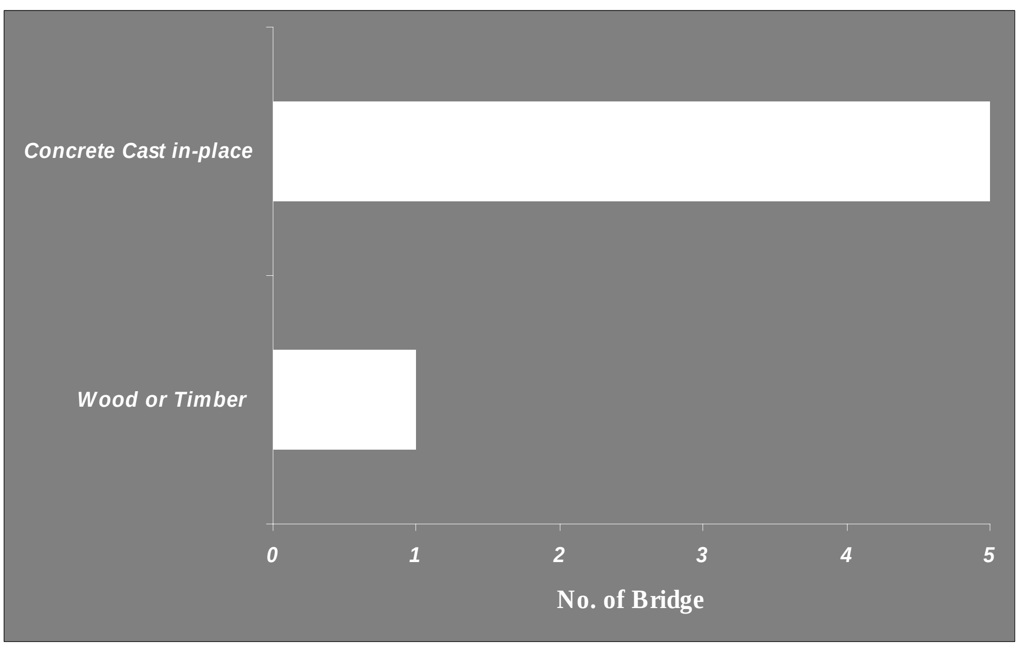


Figure 4-29 Deck structure types

In the case studies, only two deck structure types – (i) Wood or Timber and (ii) Concrete cast-in-place – were replaced by FRP bridge deck panels (Refer to Figure 4-29). This is somewhat similar to the results obtained from the questionnaire survey sent to DOT bridge engineers in that the FRP bridge deck panels were mostly used in the two deck structure types (Refer to Figure 3-5).

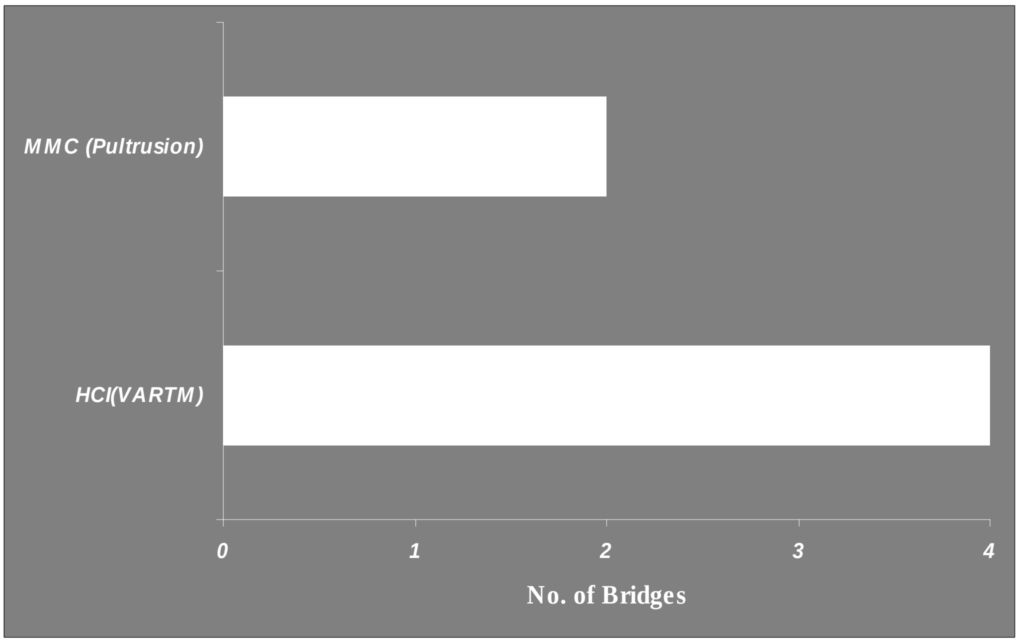


Figure 4-30 Manufacturer and manufacturing method

(3) Manufacturer and manufacturing method

As mentioned in section 4.2, only two manufacturers were involved in Project 100 and C4I. Two bridges used MMC product made by Pultrusion and four bridges used HCI product made by Vacuum Assisted Resin Transfer Molding (VARTM) method (Refer to 4-30). The result is also in accord with that obtained from the questionnaire survey sent to the DOT bridge engineers. The FRP bridge deck panels of HCI and MMC among several manufacturers were used by many DOTs (Refer to Figure 3-10).

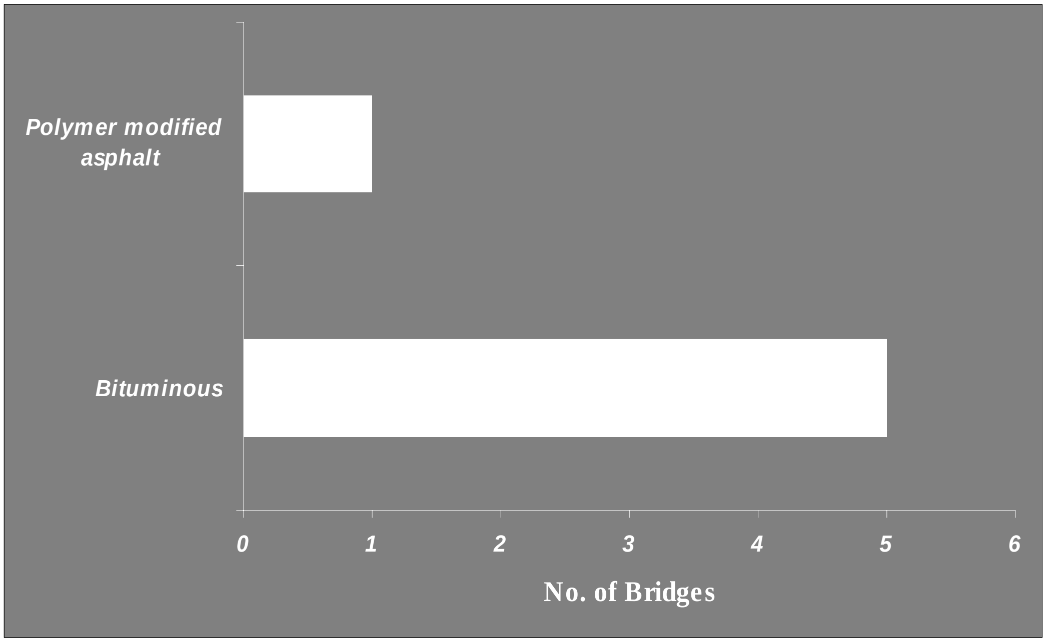


Figure 4-31 Material types of wearing surface

(4) Wearing surface

Most of the bridges used 'Bituminous' as wearing surface and only one bridge used 'Polymer modified asphalt' (Refer to Figure 4-31). In case of DOTs, 'Bituminous' was used by 7 DOTs, followed by Polymer concrete used by 5 DOTs (Refer to Figure 3-15).

(5) Installing method of guardrail

There are two methods for installing guardrail: (i) attach concrete barriers or steel guardrail to deck, and (ii) cantilever guardrail from girders. The two methods were used to install guardrail in the identified case studies. It was found that 'Guardrail attached to deck' was a preferable method (Refer to Figure 4-32).

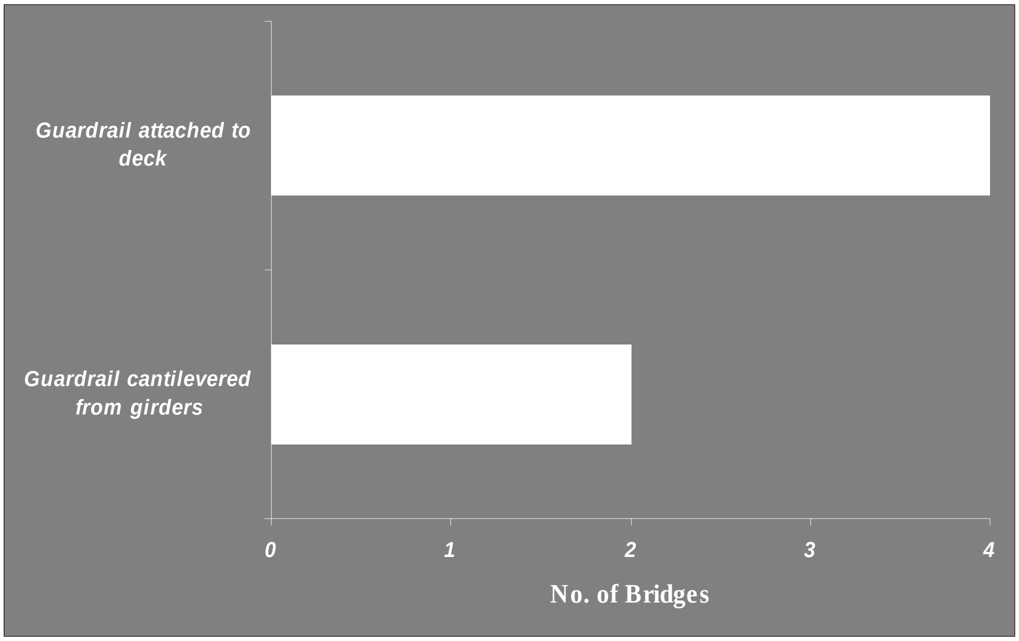


Figure 4-32 Installing method of guardrail

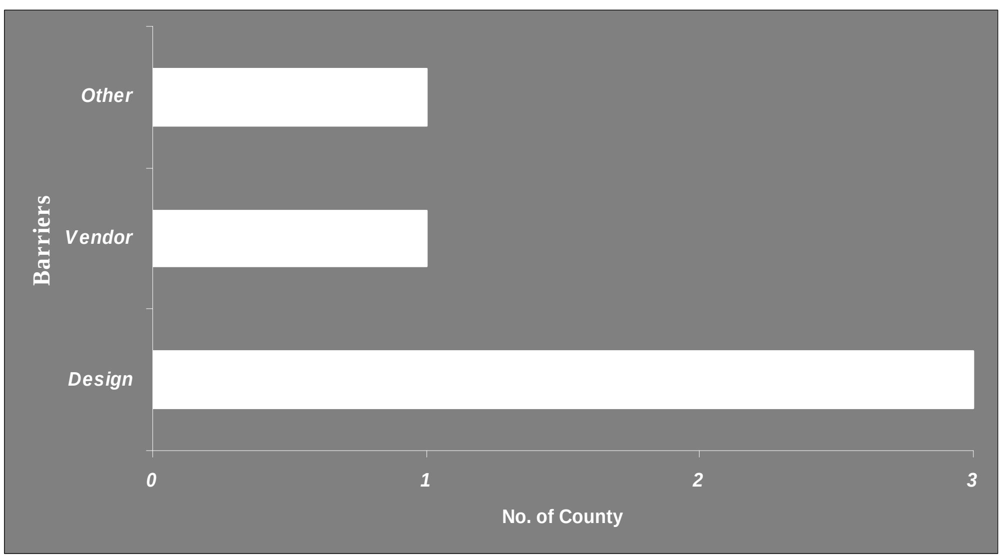


Figure 4-33 Barriers encountered in stalling FRP bride deck panels

(6) Barriers encountered in installing FRP bride deck panels

County engineers recognized that design barriers were the greatest problem out of barriers encountered in installing FRP bridge deck panels. Their opinion was similar to the opinion of the DOT bridge engineers responding to the questionnaire.

(7) Condition rating of existing bridge structures

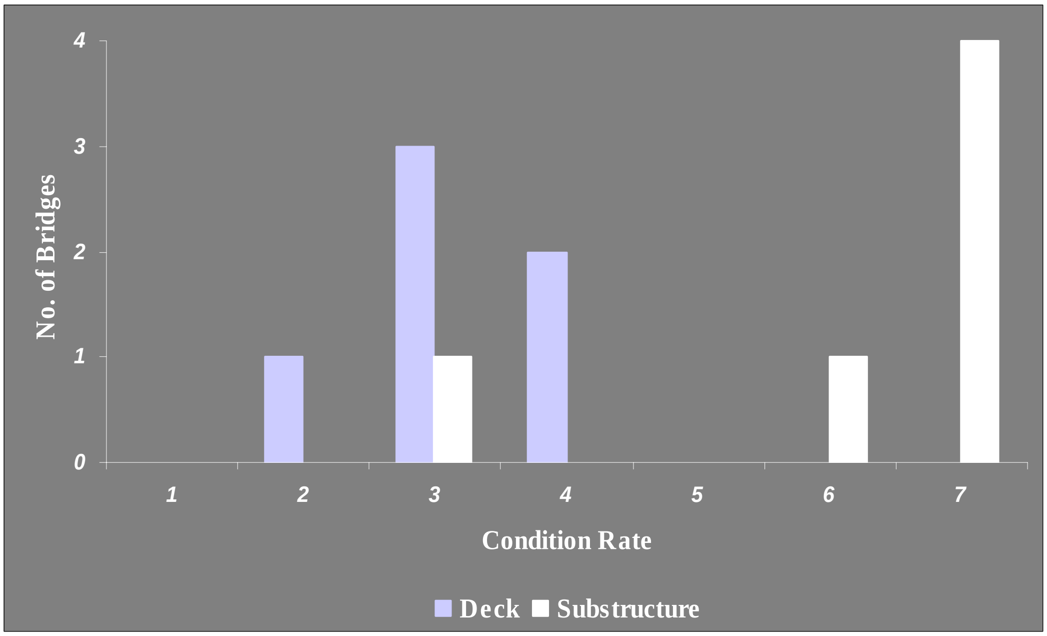


Figure 4-34 Condition rating of existing bridge structures

The condition rate (CR) of existing decks ranged from 2 to 4 when the FRP bridge deck panels were considered to replace the deteriorated conventional decks. A CR of 2-4 implies “structurally deficient”, one of two modes of bridge failure defined by the Federal Highway Administration (FHWA). According to FHWA, if one of the three load carrying component (deck, superstructure, and substructure) of a bridge receives a condition rating of less than 5 on a scale of 0 – 9, then the bridge is considered to be “structurally deficient”. The condition rating of substructure was ranked relatively high unlike the deck.

4.5. Manufacturer for FRP bridge deck panels

The purpose of visiting manufacturer of FRP bridge deck panels was to collect information on the constructability, maintainability, operability, and life cycle cost issues from the perspective of the manufacturers as well as their manufacturing process and to compare them with results obtained through the questionnaire survey-I. The research team visited two manufacturing facilities (MMC and HCI) and interviewed their engineers on February 25 and 26. 2004. To achieve the purpose, questionnaire-II was used (refer to Appendix B).

4.5.1 Hardcore Composites Inc.

Interview Highlights/Observations and Questionnaire-II

- Interviewee: Jeff Pote
- Position/Title: Senior Composite Engineer
- Address: 618 Lambsons Lane
- E-mail: jpote@hardcorecomposites.com

(1) General information of FRP bridge deck panels

- Typical size of FRP Panel: 32 feet by 20 feet
- Within the next year, one system has been scheduled and six other projects are in the initial stages of development
- Expected service life of FRP bridge deck panels produced: 75 years
- Information on completed projects

- A total of 28 projects
- All of the bridges are designed for L/800 deflection criteria.
- Design loads are variable depending on each project.

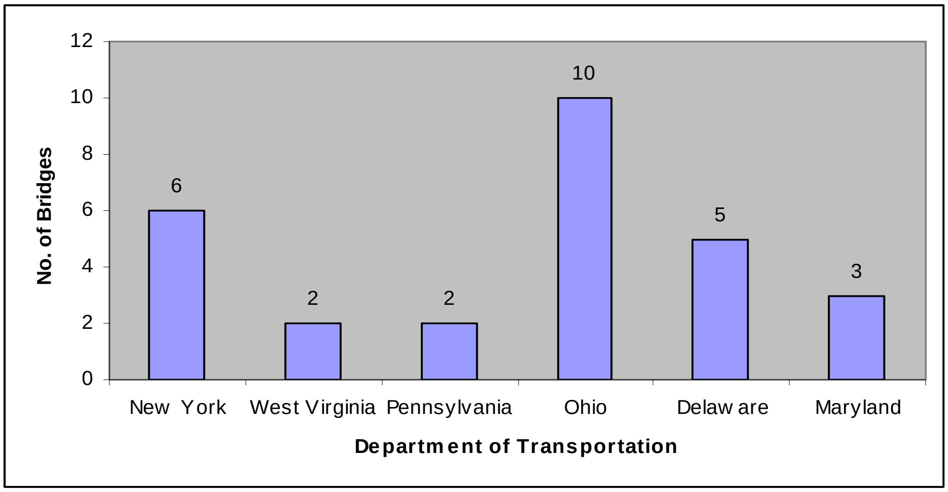


Figure 4-35 Number of bridges for DOTs using HCI's FRP bridge deck panels

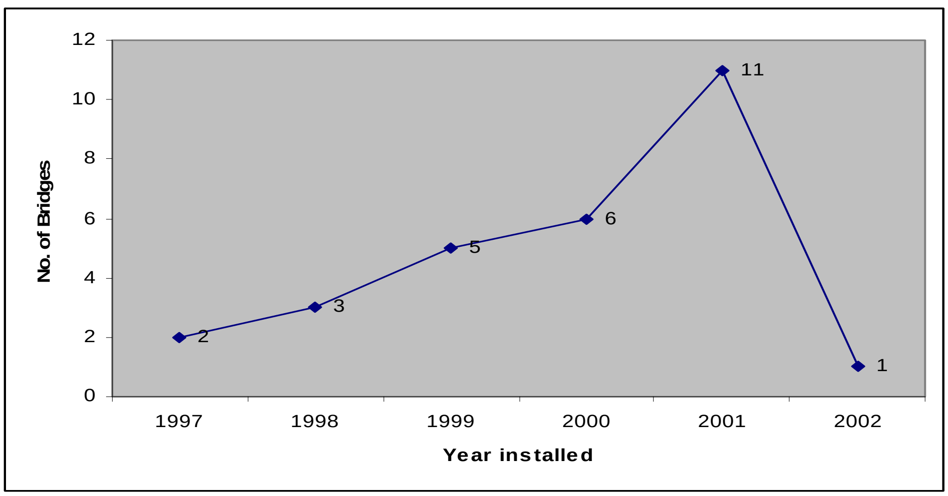


Figure 4-36 Number of bridges versus installed Year of HCI's FRP bridge deck panels

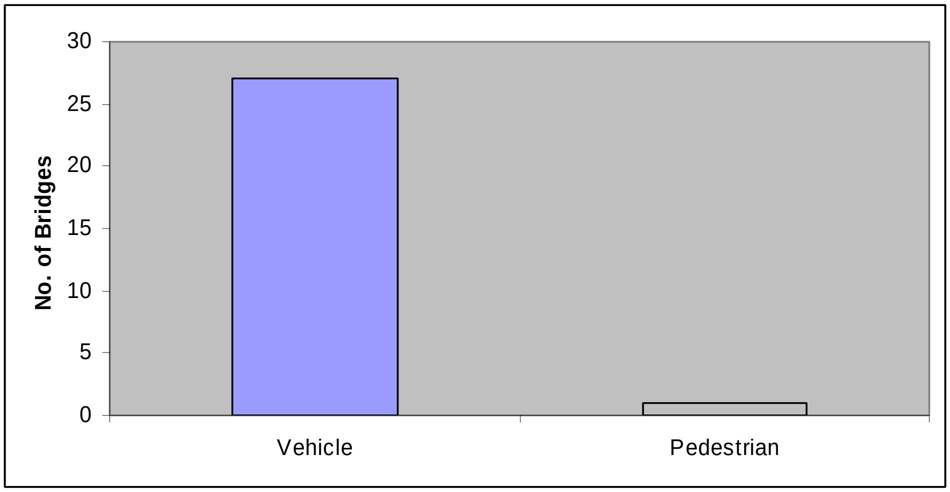


Figure 4-37 Number of vehicle and pedestrian bridges

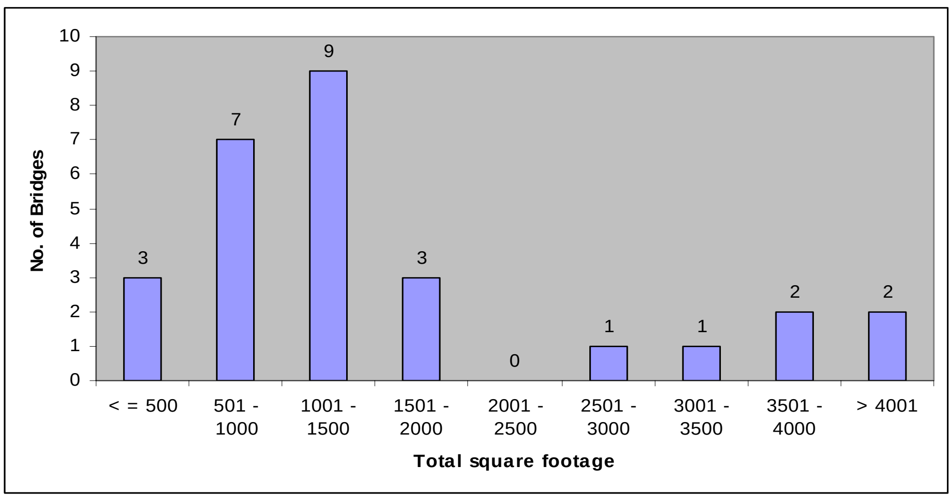


Figure 4-38 Number of bridges based on total square footage

(2) Constructability issues of FRP bridge deck panels

- Wearing surface:
  - Asphalt seems to work best for their bridge decks. However, polymer concrete and latex modified concrete have also been successfully applied to their deck systems based on the interview with their senior composite engineer (Refer to Figure 4-39).

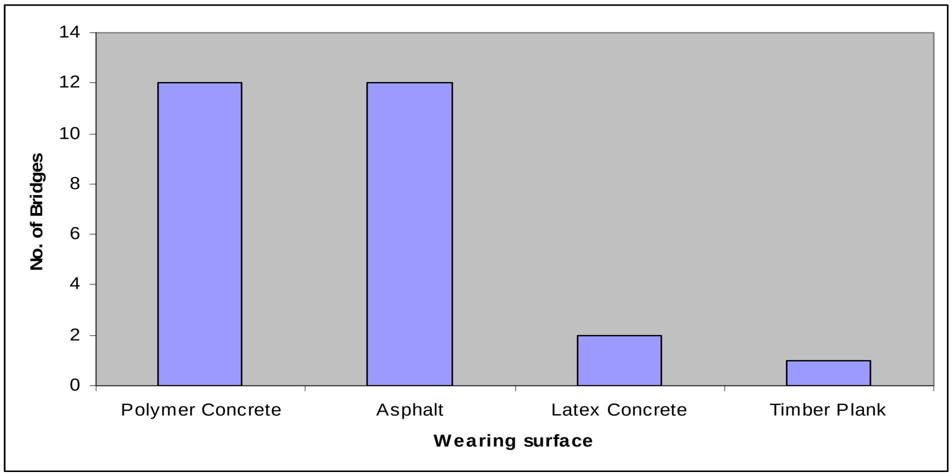


Figure 4-39 Number of bridges according to wearing surface

- Typically recommends the use of polymer concrete or latex modified Portland cement concrete.
- Polymer concrete overlays are comprised of either epoxy or polyester resin mixed with hard, sound aggregate with a particle gradation meeting ASTM C33 specifications.
- For decks accepting polymer concrete, they fabricate the top of the deck with a textured surface that provides mechanical interlock with the polymer concrete.
- So far, they have been using asphalt and they have not encountered any problems.

- Construction specification: They design bridges to meet ASSHTO codes for concrete and steel bridges
- Warranty issue

- They warranty their decks for 20 years against the following types of damage: (i) delaminations, (ii) UV degradation, (iii) fatigue induced failures, (iv) salt and deicing chemical damage, (v) deflections in excess of the bridge rating, and (vi) excessive stress under rated loads
- They do not warranty their decks against the following items; (i) acts of God, (ii) vandalism, (iii) overloading, (iv) damage from snow plowing, (v) lack of preventive maintenance, (vi) improper installation or modification, and (v) damage occurred during the placement or shipment of the decks

- Types of thermoset resin of FRP bridge deck panels
  - Hardcore Composites uses Vinyl Ester Resin since the resin system has been tested for exposure to chemicals, is very easy to process, and is less expensive than either epoxy or phenolic resins. It is also quite strong when compared with polyester and Phenolic resins (Busel and Lockwood 2000, Rivera and Karbhari 2002, Mouritz and Mathys 1999)
- Types of Fibers
  - Fiberglass is used because E-glass is inexpensive as compared to carbon and aramid and it gives the material properties required in the designs.
- Guardrail construction method
  - Most of the bridge decks that Hardcore Composites installs with guardrails are either attached to the side of the deck panel or through bolted onto the top of the deck panel. Concrete parapets have been poured onto the deck panels with rebar embedded into the FRP deck panels.

- The concrete parapets have been tested at Lehigh University to check the failure mechanism and design limits of the embedded rebar. The guardrail systems have been designed with factors of safety and are stamped by a Professional Engineer. Hardcore Composites has performed tests on steel embedment pullout strengths and composite bolt bearing tests, so that these values can be used when calculating the limits of a guardrail system.

- Types of equipment required for installation of FRP bridge deck panels
  - Typically a crane (the size of the crane depends on the bridge) and basic construction tools (impact wrench, hand tools) are the only equipment needed.
- Types of crews required for installation of FRP bridge deck panels
  - Hardcore Composites sends a crew of 2-3 men for the installation of the bridge deck. Hardcore Composites will supervise the installation and will perform any bonding tasks that are associated with the installation. A standard crew of 2-4 men can install FRP deck. The crew needs to have rigging experience in order to place the panels, but no other formal training beyond basic construction techniques is required.
- Productivity expected from the crew mentioned above
  - A normal installation of a Hardcore Composites FRP Bridge will typically take 2-5 days depending on the complexity of the bridge. A basic construction schedule is shown below.
    - Day1 – Panels placed, panels attached to stringers or abutment.
    - Day 2 – Wearing surface applied.

            - Day 3 – Guardrails attached and other work completed.
    - Major obstacles in FRP panels' application
        - Factors that influence the use of composite bridges include the high initial cost, low bidding practices, and lack of confidence or acceptance in the market place. Codes that are written for concrete and steel materials and not to maximize the properties of the composite materials are also a hindrance to the use of FRP decks.

(3) Operability issues of FRP bridge deck panels

- Effect of fuel, oil and grease on FRP deck
    - The resin system used by Hardcore Composites has been tested for exposure by the resin manufacturer for many different chemicals. These chemicals include gasoline and diesel fuel, for which the resin system is recommended for short-term exposure (24hrs). Hardcore Composites has also performed tests with diesel fuel and saw no significant decline in material properties.
- Procedure of snow removal
    - Hardcore Composites' bridges can be plowed just like a normal bridges
- Water drainage installed in FRP bridge deck panels
    - Water drainage systems used on Hardcore Composites' bridges include gutters, scuppers, grading the wearing surface, drip edges, and curbs. All of these systems are specified by the county or DOT that is purchasing the bridge.

(4) Maintainability issues of FRP bridge deck panels

- Generally recommended maintenance practices
  - Hardcore Composites typically issues a maintenance manual for their bridge decks. The maintenance manual outlines the procedures for inspecting the deck and for small repairs (refer to Appendix D). They do not provide assistance in maintaining the deck unless a warranty issues arises. They will offer engineering assistance if major damage or repairs are to be completed to the FRP bridge.
- Maintenance problem:
  - Delamination and unbonded areas in panel skin
    - Delaminations caused during the manufacturing process and injected with an adhesive.
    - Poor field connections need to be replaced or altered. Typically this repair is covered by warranty
    - Typically repairs are made in the shop at Hardcore Composites and will not appear again in the field
    - Hardcore Composites has also changed resin systems and this seems to have eliminated delaminations in the shop.
    - Connection issues will continue to arise until all the connection issues are solved (i.e., Salem Avenue Bridge)
  - Deck-to-girder connection at haunches: No Problem
  - Field and shop joint problem: No Problem, except for wearing surface

- Polymer wearing surface deficiencies: The reason for this is poor surface preparation, bad lots of material, and poor engineering.
    - Typically, the wearing surface is removed either entirely or just the bad sections and a new wearing surface is applied.
    - If the surface is not sandblasted properly the wearing surface can peel off. Also, a wearing surface that is partially shop applied and field applied can cause problems if there are too many joints.
    - Typically this repair is covered by warranty.
    - Usually 1 or 3 trips are required to repair the problem.
- Water intrusions and Fire damage: No Problem

- Procedure or method established to inspect, maintain, and repair
  - They provide a maintenance manual with every deck they sell. The manual provides general guidelines for inspection the bridges and some specific techniques that may be employed to verify the structural integrity of the bridge. The manual also includes several repair techniques. Structural repairs that need to be performed to the bridge are always to be approved by an engineer. A copy of a typical maintenance manual is attached to the Appendix D.
- In collecting inspection data on completed projects
  - They did not collect the data but the bridge installed over Dubois Creek in Susquehanna County is monitored by Penn State University.
- They have identified problems with regard to maintenance and operation after installation.

- They have not experienced the replacement of partial section in FRP bridge deck panels.
- They expect that their FRP bridge decks will last with minimal maintenance for 75 years. Environmental tests have been performed on samples of FRP panels that allow them to use environmental knock down factors when designing a bridge.

(5) Life cycle cost issues of FRP bridge deck panels

- Average initial construction cost
  - Hardcore Composites FRP bridges can cost $75/ft^2 for an 8-in deck replacement to $180/ft^2 for a complete self-supporting structure. Hardcore Composites gives a designed and delivered price, but does not include the cost of the installation for the county or contractor
- Steps (as in research or technology) to reduce high initial cost
  - Hardcore Composites has performed various tests with different bridge designs, which are patented and proprietary. Ten years of test data have been used in order to lower costs and increase the capacity of the decks.
- Currently best method to reduce high initial cost
  - Material costs are too high and standards are not written for composites, which do not allow engineers to utilize the benefits of composite materials. Also qualification of each system for a new state or county is one of the main factors that cause FRP decks to have high initial cost.

- Major reasons for high initial cost (i.e., manufacturing, delivery, size etc.)
    - Manufacturing and the cost to qualify or assure the new customers that an FRP bridge will work.
    - Too much time needed before starting a project.

4.5.2 Martin Marietta Composites

Interview Highlights/Observations and Questionnaire-II

- Interviewee: Matthew K. Sams, (PE)
- Position/Title: Senior Engineer
- Address: 2501 Blue Ridge Rd, 5th Floor, Raleigh, NC 27607
- E-mail: matt.sams@martinmarietta.com

(1) General information of FRP bridge deck panels

- Advantage of their product: Light weight, corrosion resistance, rapid installation, easy to fabricate, handle, and install, and high quality manufacturing procedure
- Expected service life of their product: It depends on the installation but 75 years is considered as the expected service life.
- They have 26 bridge decks in service and each is a unique application.

(2) Constructability Issues of FRP bridge deck panels

- Wearing surface: The material for the wearing surface is decided by owner's preference.

- Construction specification: They provide recommended installation procedures at planning meetings, pre-bid meetings, pre-construction meetings, and they provide on-site technical assistance during installation. They also provide contractors with an installation guide.
- Warranty issues: They stand behind their product. In the beginning, people requested warranties because the material was not tried and true. Now most are comfortable with the backing of their organization. Warranties are not frequently required now, but they are willing to consider if required by owner.
- Problem encountered in installing: Their main barrier is initial concern regarding "new" materials. Once people see, touch, and fell their products, they realize that is quite easy to install
- Types of thermoset resin: Many resins have been used. With their system, polyester resin typically provides best value.
- Types of Fibers: Many fibers have been used. With their system, glass fiber typically provides best value
- Railing construction method: Owner's preference. Railing has been attached a variety of ways
- Types of equipment: Cranes, jacks, etc.
- Types of crew: They typically recommend a minimum of 6 person crew (8 – 10 preferred). No special skills are required
- Productivity expected: It is not uncommon to install each of their panels in 30 minutes or less

- Major obstacle in the application: High initial cost, current low bidding practice in the US, lack of material and design specification, etc.

(3) Operability of FRP bridge deck panels

- Effect of fuel, oil and grease: Their decks typically are covered by an overlay, which would receive the spills. Detailed information can be provided on a site specific basis
- Procedure of snow removal: Their decks typically are covered by an overlay, which allows snow plows and studded tires.
- Effect by salt and other chemicals: Their decks are resistant to corrosion induced by deicing salts
- Water drainage: All of the following are possible: crowned overlay, crowned deck, scuppers, curbs, super elevations, etc.

(4) Maintainability of FRP bridge deck panels

- The responsibility for the maintenance problem: Like all materials, the owner has responsibility
- General maintenance practices recommended: Nothing very unique. Keeping an eye out for anything that appears out of the ordinary. Most "issues" will be reflected in overlay.
- They provide assistance in the maintenance activities
- They often participate in the first inspection of the bridge
- They have not experienced the replacement of partial section in their products

4.6 Reference

Busel, J. P. and Lockwood, J. D., eds. (2000). *Production selection guide: FRP composite products for bridge applications*, Market development Alliance (MDA) of the FRP composites industry, Harrison, NY.

Mouritz, A. P., and Mathys, Z. (1999). "Post-fire mechanical properties of marine polymer composites." Composites Structure, 47(1), 643-653.

Reeve, Scott R. (2000). "FRP Composite Bridge Decks: Barriers to Market Development" National Composites Center, Kettering, Ohio.

River, J., and Karbhar, V. M. (2002). "Cold-temperature and simultaneous aqueous environment related degradation of carbon/vinylester composites." Composites Part B: Engineering, Elsevier Science Ltd., 33(1), 17-24.

Project 100 <http://www.compositecenter.org/Infra/Project%20100/Project%20100.php> (March 22, 2004.)

CHAPTER 5: PROCESS MODELING AND SIMULATION

5.1 Introduction

Process modeling and simulation study were used to determine the productivity of installation in both FRP bridge deck panels and conventional bridge deck (precast concrete deck) construction. Installation procedure for the two methods was carefully evaluated to develop the initial process model. Simulation study was conducted using web-based MicroCyclone simulation software (Halpin and Riggs 1992). The data required for the simulation study were collected through questionnaire survey and interview. For simulation study of FRP bridge deck panels, the installation procedure of Martin Marietta Composites (MMC), which was selected in Composites for Infrastructure (C4I) program, among various manufacturers was analyzed to determine their productivity. In order to make a comparative study of the productivity for FRP bridge deck construction, construction method of precast concrete deck panels was used as one of the methods of conventional bridge deck construction. This chapter describes the simulation study by first explaining the background of CYCLONE and WebCYCLONE followed by the construction procedure of the two types of panels (i.e., FRP and precast concrete), as well as the data collection.

5.2 Simulation study using WebCYCLONE

This research used CYCLONE (CYCLic Operations Network) simulation methodology, which simplified the simulation modeling process, and made it accessible to construction practitioners with limited simulation background (Halpin and Riggs 1992). The CYCLONE became the basis for a number of construction simulation systems. The WebCYCLONE is Web based simulation tool which generates CYCLONE formatted simulation code from information collected through its web based interaction with the user. For the modeling of construction processes, the following procedure is required:

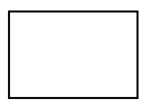
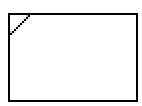
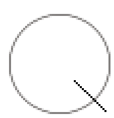
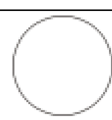
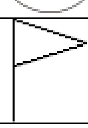
1. Define *resources* which are used to process work task such as equipment, manpower, material, etc.
2. Identify *work tasks* in the processes. The work tasks mean fundamental field action and work unit focus, intrinsic knowledge and skill at crew member level, and basis of work assignment to labor.
3. Determine the logic of the processing of resources
4. Build a model of the process: Basically, in order to simulate the actual process, resource, work task, and time consumed by processing the resource are required.

The CYCLONE methodology primarily consists of four basic phases (Schaeuble 2001)

1. Identify the flow units in the cycles: The flow units represent the units that are relevant or descriptive for the process to be modeled. These units usually mean resources.

2. Develop the cycles for each flow unit: For modeling the flow cycle of a unit, all the possible active and passive sates should be considered.
3. Integrate the flow unit cycles: Each flow cycle is integrated into an entire model and it usually is linked together at COMBI nodes.
4. Initialize the flow units: The flow units should be initialized in number and in initial location to analyze the model and are always initialized at waiting positions, QUEUE nodes.

Table 5-1 Basic modeling elements of the CYCLONE

Name	Symbol	Function
Normal Activity		This is an activity similar to the COMBI. However, units arriving at this element begin processing immediately and are not delayed.
Combination (COMBI) Activity		This element is always preceded by Queue Nodes. Before it can commence, units must be available at each of the preceding Queue Nodes. If units are available, they are combined and processed through the activity. If units are available at some but not all of the preceding Queue Nodes, these units are delayed until the condition for combination is met.
Queue Node		This element precedes all COMBI activities and provides a location at which units are delayed pending combination. Delay statistics are measured at this element
Function Node		It is inserted into the model to perform special function such as counting, consolidation, marking, and statistic collection
Accumulator		It is used to define the number of times the system cycles
Arc		Indicates the logical structure of the model and direction of entity flow

(Source: Halpin and Riggs 1992)

The actual appearance of the CYCLONE model will depend on the identification and definition of the network elements (i.e., the NORMAL and COMBI) together with the associated QUEUE nodes, ARCs, and logical relationships (Halpin and Riggs 1992). These symbols are the basic modeling elements of the CYCLONE modeling systems and are shown in Table 5-1. For the detailed understanding of the CYCLONE, please refer to Halpin and Riggs (1992).

5.3 Installation Procedure

As mentioned in the previous section, simulation study using CYCLONE requires an understanding of the construction process of FRP bridge deck panels as well as conventional bridge deck. This section introduces the construction processes for the two types of bridge deck construction.

5.3.1 FRP bridge deck panels

The installation procedure for FRP bridge deck panels varies from one manufacturer to another. The installation process used by Martin Marietta Composites (MMC) out of various manufacturers is selected in this research to do simulation study (Busel et al. 2000, Solomon and Sams 2003)

The figures below illustrate the major tasks for installation of MMC FRP bridge deck panels. Installation procedure of MMC is categorized in two parts: (i) manufacturing procedure and (ii) installation procedure at the job site (Figure 5-1).

(1) From the viewpoint of Manufacturing Procedures:

Step 1: Individual tubes are pultruded at a manufacturing facility.

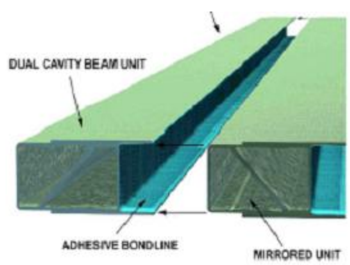


Figure 5-1 Individual tubes pultruded
(Source: Busel and Lockwood 2000)

Step 2: Assembled into panels with a polyurethane adhesive (Panels are typically 8 to 10 ft. in width due to highway transport restrictions)

Figure 5-2 Panels assembled with a polyurethane adhesive
(Source: Busel and Lockwood 2000)

Step 3: The bonded panels are sent to a finish shop, where all secondary work (hole cutting and sealing, installation of close outs, surface finishing, etc.) is performed.

Step 4: Finished Panels to be loaded

Figure 5-3 Panels finished for loading
(Source: Busel and Lockwood 2000)

Step 5: Panels Transported to Job Site

Figure 5-4 Panels Transported to Job Site

(Source: Busel and Lockwood 2000)

(2) From the viewpoints of Installation Procedures at Job Site

Step 1: Panels being unloaded

Figure 5-5 Panels being unloaded
(Source: Busel and Lockwood 2000)

Step 2: Installation of First Panels

Figure 5-6 Install first panels

(Source: Busel and Lockwood 2000)

Step 3: First Panel Installation and Alignment

Figure 5-7 Install and align first panel
(Source: Busel and Lockwood 2000)

Step 4: Securing the Deck Utilizing Temporary angles on Top Flanges

The large circular holes in the edge of the deck provides access for placing reinforcing steel and pouring concrete in the last tube in order to accommodate an integral abutment

Figure 5-8 Securing of the deck
(Source: Busel and Lockwood 2000)

Step 5: Liquid Primer and Epoxy Paste Being applied to Field Joints

Figure 5-9 Liquid primer and epoxy paste applied to field joints
(Source: Busel and Lockwood 2000)

Step 6: Lowering of the Next FRP bridge deck panels

Figure 5-10 Lowering of second panel
(Source: Busel and Lockwood 2000)

Step 7: A jack is used to align the panels in position

Figure 5-11 Align the panel using a jack
(Source: Busel and Lockwood 2000)

Step 8: FRP Splice Strips Placement Over Field Joints

The FRP splice strips are installed to ensure a durable and watertight joint.

Figure 5-12 Place FRP splice strips over field joints
(Source: Busel and Lockwood 2000)

Step 9: Finished Panel installation

Figure 5-13 Finish panel installation
(Source: Busel and Lockwood 2000)

Step 10: Connections between deck and girder

Shear studs are field welded after the deck panels are in place, and grout is poured in the cavity

Figure 5-14 Connect decks with girders

Step 11: Guardrail Installation (Concrete barrier or steel guardrail)

Figure 5-15 Install guardrails

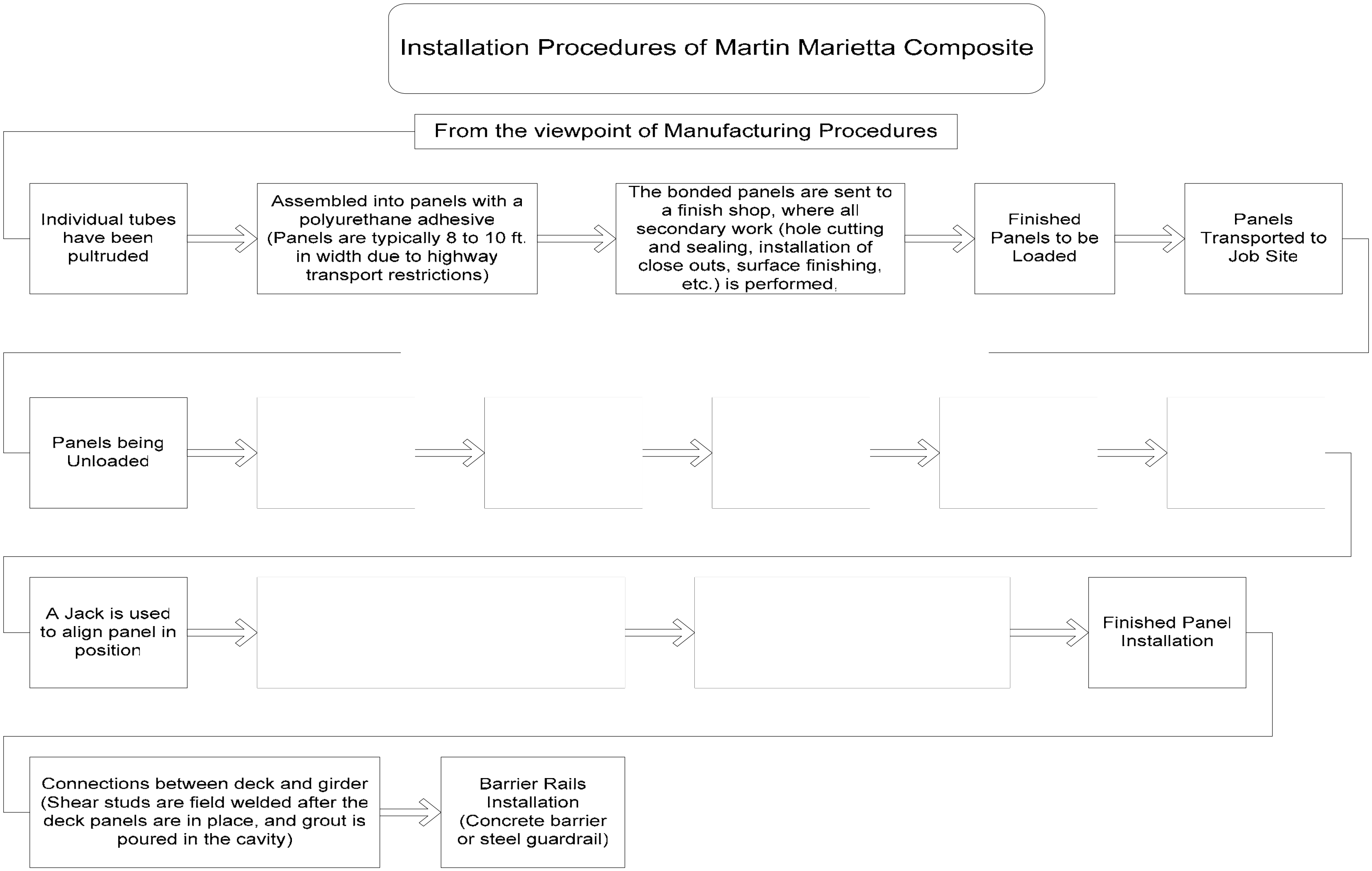


Figure 5-16 Installation procedure of MMC

5.3.2 Precast prestressed concrete deck panels

The following procedures is used for the installation of precast prestressed concrete deck panels. After the erection of the structural members and the tightening of all bolts, the contractor takes measurements to record the elevations at predetermined grade control points along each girder of each span in the structure. Any falsework of forms should be installed before deck forms are installed. There are two types of deck forms: (i) Removable and (ii) Permanent.

(i) Removable: Most removable forms are made of wood

(ii) Permanent: Permanent forms are usually made of metal or Prestressed concrete. Another type of permanent deck forms is precast, prestressed deck panels. When they are used, the bottom layer of longitudinal deck may be unnecessary because the panels contain their own longitudinal reinforcement.

The construction sequence employed at Cape Girardeau Bridge, Cape Girardeau, Missouri is introduced in this section and used for the construction simulation study of this method.

Figure 5- 17 Cape Girardeau Bridge, Cape Girardeau, Missouri

Project description

The project was to build cable-stayed bridge over the Mississippi River connecting Cape Girardeau, Missouri, and East Cape Girardeau, Illinois. The bridge is composed of one main span (1,150 feet) and two side spans (468 feet). The width of the bridge is 86 feet and 4 inches (Cape 2004).

- Contractor: Traylor Bros., Inc.
- Project manager: Larry K Owens
- Project engineer: Skylar Lee
- Amount of concrete used: Approximately 50,000 CY.
- Place more than 3,200 tons of rebar, 41,000 tons of structural steel, 12,800 tons of post-tensioned precast concrete deck panels, and 128 stay cables
- Wearing surface: 3 inches silica fume concrete
- Project duration: June 1. 2000 – December 13.2003

Cape Girardeau Bridge was composed of two different types of bridges and deck panels ((Larry K. Owens, personal communication, April 2004)

- One type was very large deck panels (approximately 45 feet × 15 feet × 1 foot) and they were used to make the deck of the cable stayed bridge portion of the project
- The other deck panels were more conventional and used in an application that is more similar to the FRP bridge deck panels' situation. Those deck panels were about 4 inches thick. They were made of conventional concrete and prestressed with strand. The top surface was textured to

facilitate a bond with the poured in place portion of the bridge deck. The panels were also fitted with rebar loops that were used to lift the panels and also to help make them composite with the cast in place concrete. In the conventional deck panel scenario in which the relatively thin deck panels first act as bottom forms for the deck construction and then become composite with the 5 inches of concrete poured on top

Construction procedure

The construction procedure of Precast prestressed concrete deck panels used on the project is as follows.

(1) Panels transported to job site.

(2) Lay down styrofoam filler strips on the top flanges of the steel plate girders

(3) Panels being unloaded: The panels are delivered to the site and stacked onto the trucks in the proper order so that they can be lifted off of the truck and set directly into position.

(4) Install first panel

(5) Align first panel

(6) Repeat (4) and (5) until all panels are installed

(7) A layer of epoxy-coated rebar is then installed for a 5 inches thick conventionally placed bridge deck

(8) Pour concrete for the 5 inches thick conventionally placed bridge deck (Concrete deck pours were made using conventional truck mounted concrete pumps and Bidwell machines to finish)

(9) Guardrail is installed after the panel erection is finished

5.4 Data collection

5.4.1 Data for simulation of FRP bridge deck panel construction

The data for simulation study using WebCYCLONE were collected through questionnaire-III. The required data include the duration of each task (man-hour requirement), resource inputs such as major equipment, material, etc., and the number of labors. Questionnaire-III is composed of two parts that include:

(1) Part 1: Duration (Minutes) – How much time was needed to finish a certain work (work tasks)?

(2) Part 2: Resource – How many labors were necessary to finish a certain work (work tasks)? What major equipments were required?

The original version of questionnaire-III is attached in Appendix C. The questionnaire was mailed to Defiance and Greene Counties in Ohio. These counties have used FRP bridge deck panels made by MMC called DuraSpan. The cost data of equipment and labor were collected through interview.

(1) Duration and resource data

- Deck dimension for Greene County (Fairgrounds Road Bridge): 227 feet * 32 feet 6 inches
- Total square footage: 7400’20’’
- Deck Depth: 8 inches

- Number of FRP bridge deck panels used /span: 28
- Panel size: 32’6’’ long and 8’ wide

In collecting activity duration data for FRP bridge deck panel construction, triangular distributions were used. The main benefit of a triangular distribution is simplicity and it is easy and straightforward to collect data (Moder et al 1983).

The duration and resources data for the activities represented in the simulation model of FRP bridge deck panels were collected from the county engineer of Greene County, OH, as shown in Tables 5-2 and 5-3.

Table 5-2 Duration input data of FRP bridge deck panels

Node No.	Work task	Duration (Minutes)		
		Minimum	Most Likely	Maximum
4	Unload the panels on the job site	10	15	20
6	Life one panel by using a crane (Panel size: 32’6’’long 8’ wide)	2	4	6
9	Place one panel into a girder by using a crane	10	15	20
12	Align one panel into position by using a jack	15	20	25
16	Install the FRP dowel bars in the lips of the field joints	1	2	5
18	Install FRP splice strips in the lips of the field joints	45	60	90
21	Install shear studs to connect between decks and girders	30	45	60
24	Pour grout in the cavity	30	45	60
27	Install guardrail	900	960	1020

Table 5-3 Resource input data of FRP bridge deck panels (Labors and equipment)

Work tasks	Number of labors & equipment
Finish the placement and alignment of panels	5 labors, 1 crane and 1 jack
Finish the installation of the FRP dowel bars	1 labors
Finish the installation of FRP splice strips	2 labors
Finish the connection between decks and girders	1 labor for shear studs & 5 labors and grout pump for grout
Finish the installation of the guardrail	3 labors

(2) Cost data

Hourly equipment costs were derived from the assumption that equipment operates eight hours per day and the total costs of equipment including operation cost were calculated. The hourly rate in 2001 at Midwestern area of USA (75 $/hr) was considered as the hourly labor cost. The equipment cost data were obtained by interview with a contractor of Fairgrounds Road Bridge project (Table 5-4).

Table 5-4 Equipment costs of FRP bridge deck panels' construction

Equipment	Hourly equipment cost ($)
Truck mounted, Crane	$ 125/hr
Grout pump	$ 175/hr
Shear stud gun	$ 175/hr

5.4.2 Data for simulation of Precast Concrete Panels

The data required for simulation of Precast Concrete panels were obtained through interview with the project manager and engineer of Cape Girardeau Bridge project.

- Total square footage: 110, 500
- Deck Depth: 4 inches
- Number of FRP bridge deck panels Used /span: 1404
- Average Panel size: 10' long and 8' wide

The duration and resource data for the activities represented in the construction simulation model of Precast concrete deck panels were collected from the project manager and engineer on the Cape Girardeau Bridge project shown in Tables 5-5 and 5-6.

Table 5-5 Duration input data of Precast concrete deck panels

Node No.	Work task	Duration (Hours)		
		Minimum	Most Likely	Maximum
3	Lay down Styrofoam	408*		
7	Panels being unloaded	4	6	8
10	Install first panel (Panel size: 10'long 8' wide)	0.25	0.5	1
12	Align first panel (Panel size: 10'long 8' wide)	0.25	0.5	1
16	Install a layer of epoxy-coated rebar	40*		
20	Pour concrete along with 5 inches conventionally placed bridge deck	5	6	7
23	Pour concrete along with 5 inches conventionally placed bridge deck	1	2	3
27	Install barrier rails in Precast concrete panel	30	45	60

*** Constant duration input (for the entire project)**

Table 5-6 Resource input data of Precast concrete deck panels (Labors and equipment)

Node No.	Work task	Number of labors & equipment
3	Lay down Styrofoam	2 Labors
7	Panels being unloaded	2 labors and 1 crawler crane
10	Install first panel (Panel size: 10'long 8' wide)	3 labors and 1 crawler crane
12	Align first panel (Panel size: 10'long 8' wide)	3 labors
16	Install a layer of epoxy-coated rebar	6 labors (Ironworkers)
20 & 23	Pour, cure, and finish concrete along with 5 inches conventionally placed bridge deck	1 pump truck, 4 finishers, and 20 labors including operators and finishers
27	Install barrier rails in Precast concrete panel	4 finishers and 2 labors

The Styrofoam betting was usually installed by a two man crew. Based on a typical day, workers would unload 6 trucks of 12 panels per truck. Each panel weighs 3500 to 4000 lbs. 130 ton class crane was used to set the deck panels. A typical crew used in setting the deck panels would be 2 men on the truck, 3 men setting the panels, and a crane operator. For the node number 16 to 23 of work task, the durations were based on a 43 feet wide deck at 170 feet length with 5 feet ½ inches Cast-in-place deck over Precast panels.

Figure 5-18 Bidwell machine
(Source: http://www.bid-well.com/3600.html)

Bidwell machines were used to finish concrete deck pours. A Bidwell machine is a motorized finishing screed that rides on a truss (Figure 5-18). The truss runs on a rail and self advances as the screed moves across the bridge. Only one crawler crane for 40 hour/week schedule was required in this project.

The equipment cost data were also obtained from the project manger and engineer on the Cape Girardeau Bridge project shown in Tables 5-7. The hourly rate in 2001 at Midwestern area of USA (75 $/hr) was considered as the hourly labor cost.

Table 5-7 Equipment costs of Precast concrete deck panels

Equipment	Hourly operation cost ($)	Hourly operator cost ($)	Total hourly equipment cost ($)
Crawler Crane	$165/hr*	$22/hr	$187/hr
Concrete pump truck	$170/hr	N/A	$170/hr
Finisher	$16.50**	$22/hr	$38.50hr

Note: *$165 = Rental rate ($90/hr) + Operating rate ($75/hr) **$16.50/hr = Rental rate ($11.50/hr) + Operating rate ($5/hr)

5.5. Simulation Model

Construction simulation models for both FRP bridge deck panels and Precast concrete deck panels were prepared based on construction procedure introduced in 5.3. Figures 5-18 and 5-19 present simulation model of both systems. Input file for FRP bridge deck panels and Precast concrete deck panels are illustrated in Appendix E and Appendix F, respectively.

The Precast concrete deck panels are similar to FRP bridge deck panels in that panels fabricated in the factory are placed in the two systems. The basic difference in both systems is that thin Precast concrete deck panels of 4 inches depth act as bottom forms for the deck construction and then become composite with the 5” of concrete poured on top. However, FRP bridge deck panels, 8 inches in depth, are directly placed on top of the girders without additional concrete pour on top.

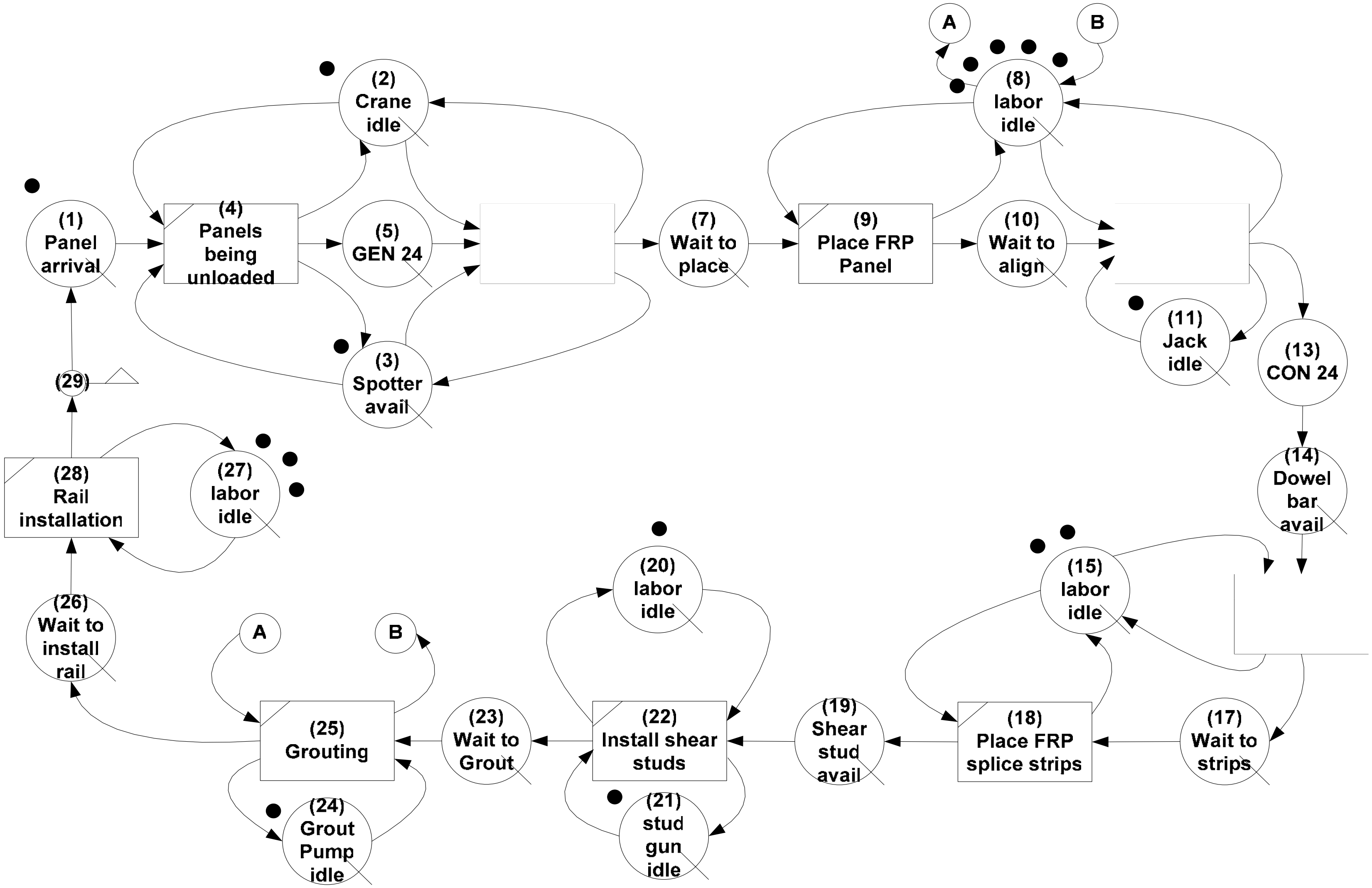


Figure 5-19 Simulation model for FRP bridge deck panels

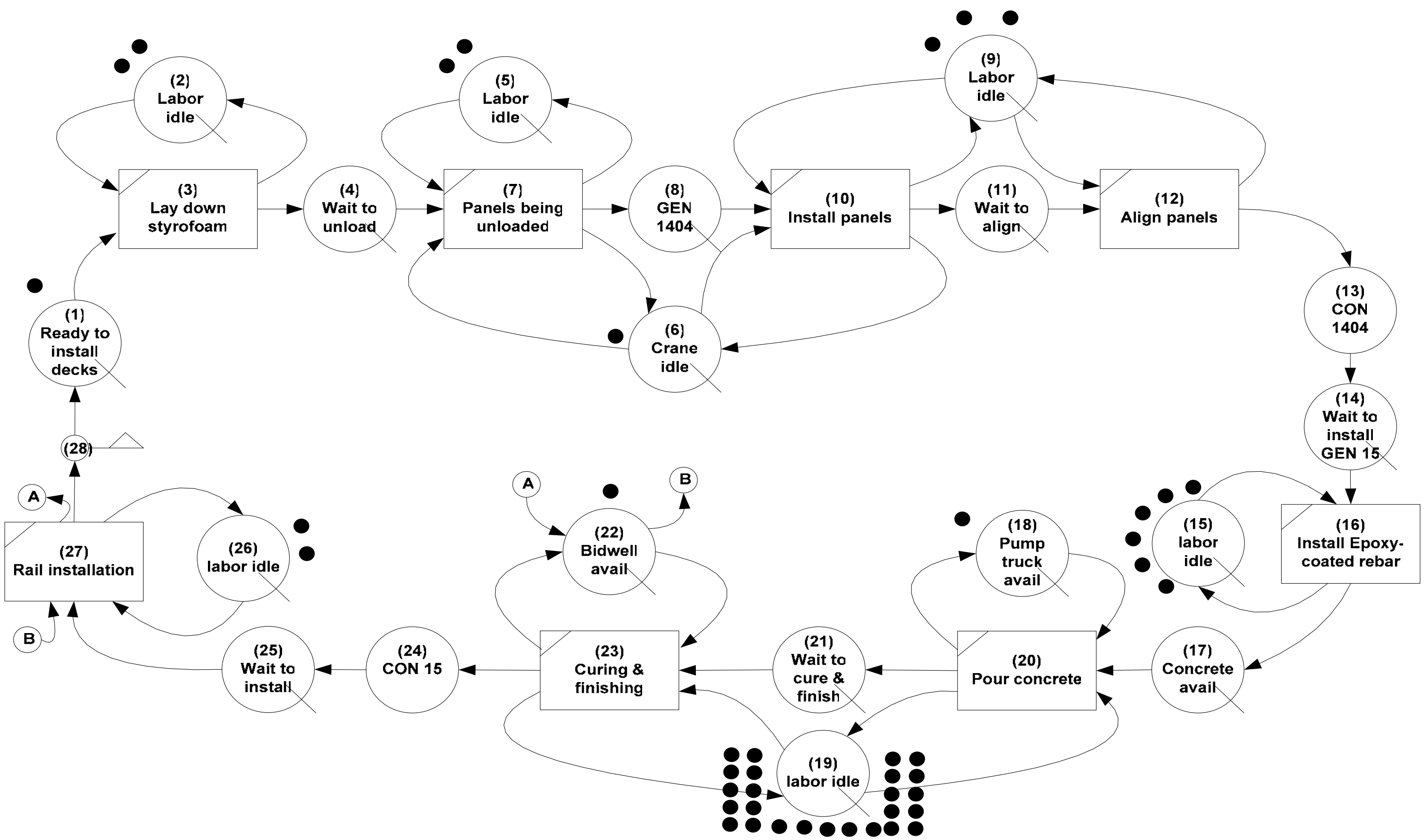


Figure 5-20 Simulation model for Precast concrete deck panels

5.6 Simulation results

Based on WebCYCLONE, the construction simulation result of a repetitive cycle in both projects was presented as the productivity. The productivity was represented as productivity per time unit. For computing productivity of both FRP bridge deck panels and Precast concrete deck panels, 'Hours' was used as the time unit (Table 5-8).

The cycle number in Table 5-8 represents the number of time both systems cycle. For instance, one cycle of FRP bridge deck panels (Refer to Figure 5-19) includes Queue node (1: Panel arrival) to accumulator (29). In case of Precast concrete deck panels (Refer to Figure 5-20), Queue node (1: Ready to install decks) to accumulator (28) is included in the one cycle of the system. It was usually defined by user. Therefore, the productivity of both systems can be calculated through dividing 'Cycle number' by 'Total simulation time (i.e., 300/7946.3 = 0.03775 for FRP bridge deck panels and 20 / 28151.1 = 0.000710 for Precast concrete deck)

Table 5-8 Simulated productivity result

	Total simulation time (unit)	Cycle No.	Productivity (per time unit)	Production/ cycle	Productivity (ft^2/hr)
FRP bridge deck panel	7946.3 (hours)	300	0.03775 (cycles/hr)	7400 ft^2	0.03775*7400 = 279.375 ft^2/hr
Precast concrete deck	28151.1 (hours)	20	0.00071 (cycles/hr)	110,500 ft^2	0.0007*110,500 = 78.5049 ft^2/hr

A total square footage of FRP bridge deck panel in the Fairgrounds Road Bridge project was 7,400 ft^2 while the Cape Girardeau Bridge project placed 110,500 ft^2 of post-tensioned precast concrete deck panels. Converting in terms of ft^2/hr, the productivity of 7,400 ft^2 of FRP bridge deck panels is 279.375 (ft^2/hr) and that of 110,500 ft^2 of Precast concrete deck is 78.5049 (ft^2/hr). Therefore, it was found that FRP bridge deck panels could produce more than three times as much productivity as Precast concrete deck panels (279.375 / 78.5049 = 3.55). In the next section, sensitivity analysis was introduced to optimize the performance of a given system by changing the resources or other conditions.

5.7 Sensitivity analysis

The objective of sensitivity analysis is to find the optimal performance of a given system by varying the resources. Changing the number of resource units in a model may affect the productivity results. The critical resources can be identified through the sensitivity analysis. The critical resources have a very small amount of idleness time in the systems and generally close to zero. Another possibility to optimize the performance is to keep maintaining the productivity but reducing the resources. This is possible in system where resources have high idleness values (Shuaeuble 2001).

5.7.1 FRP bridge deck panels

The sensitivity analysis was performed within the ranges of number of resources illustrated in Table 5-9. Only main 4 resources were considered because the change of their number might affect the productivity of the systems while the rest of resources were fixed as original units. The result of simulated productivity and the unit cost is presented in Table 5-10 and Figure 5-21.

Table 5-9 Units of various resources

Systems	Node of no.	Resource	Minimum unit	Maximum unit
FRP bridge deck panel	2	Crane	1	2
	8	Labor	2	5
	21	Stud gun	1	2
	24	Grout pump	1	2

As shown in Table 5-11, the productivities and costs per unit time (hours) for FRP bridge deck panels are variable depending on the number of resources (i.e., cranes, labors, shear stud gun, and grout pump). Within these ranges, the optimal system was one that was composed of 1 crane, 2 labors at node number 8, 1 shear stud gun, and 1 grout pump, which had the lowest cost per units ($19.25) and the lowest cost per productivity units (560.640 units/hour) . The second optimal system required 3 labors at node number 8 and the rest had same composition as the first system. It was found that the number of labors is the first major factor affecting the productivity. On the other hand, the number of other resources did not make much effect on the productivity.

Table 5-10 Simulation results based on varied resources in FRP bridge deck panels

	Resource information				Productivity information		
Scenarios Number	Crane'	Labor	Stud gun	Grout pump	Productivity Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
1	***1***	***2***	***1***	***1***	***0.0343***	***19.2460***	***560.640***
2	1	2	1	2	0.0342	22.2544	650.230
3	1	2	2	1	0.0344	22.1878	645.807
4	1	2	2	2	0.0344	25.1213	730.973
5	***1***	***3***	***1***	***1***	***0.0356***	***20.5317***	***576.690***
6	1	3	1	2	0.0355	23.3865	658.940
7	1	3	2	1	0.0356	23.4468	658.940
8	1	3	2	2	0.0354	26.4572	746.447
9	1	4	1	1	0.0369	21.7587	590.240
10	1	4	1	2	0.0370	24.7942	669.573
11	1	4	2	1	0.0369	24.7085	669.573
12	1	4	2	2	0.0368	27.5347	748.907
13	1	5	1	1	0.0376	22.9767	610.470
14	1	5	1	2	0.0377	25.9145	688.053
15	1	5	2	1	0.0376	25.8824	688.053
16	1	5	2	2	0.0376	28.9886	771.393
17	2	2	1	1	0.0343	21.3459	621.473
18	2	2	1	2	0.0343	24.2311	706.640
19	2	2	2	1	0.0343	24.2598	706.640
20	2	2	2	2	0.0343	27.1278	791.807
21	2	3	1	1	0.0356	22.6169	635.440
22	2	3	1	2	0.0355	25.5092	717.690
23	2	3	2	1	0.0356	25.5677	717.690
24	2	3	2	2	0.0356	28.5047	799.940
25	2	4	1	1	0.0369	23.8564	646.907
26	2	4	1	2	0.0369	26.7942	726.240
27	2	4	2	1	0.0368	26.7602	726.240
28	2	4	2	2	0.0369	29.7376	805.573
29	2	5	1	1	0.0377	25.1324	665.887
30	2	5	1	2	0.0377	28.0120	743.470
31	2	5	2	1	0.0378	28.0666	743.470
32	2	5	2	2	0.0377	30.9860	821.053

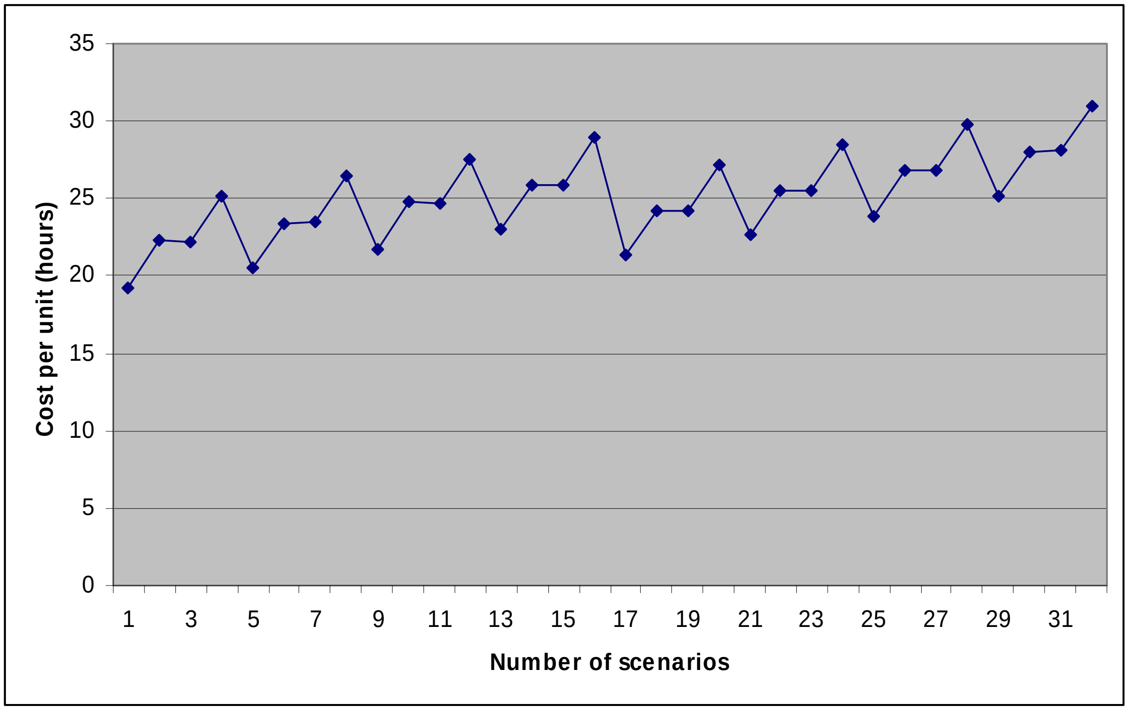


Figure 5-21 Cost per unit (hours) versus scenarios number in FRP bridge decks

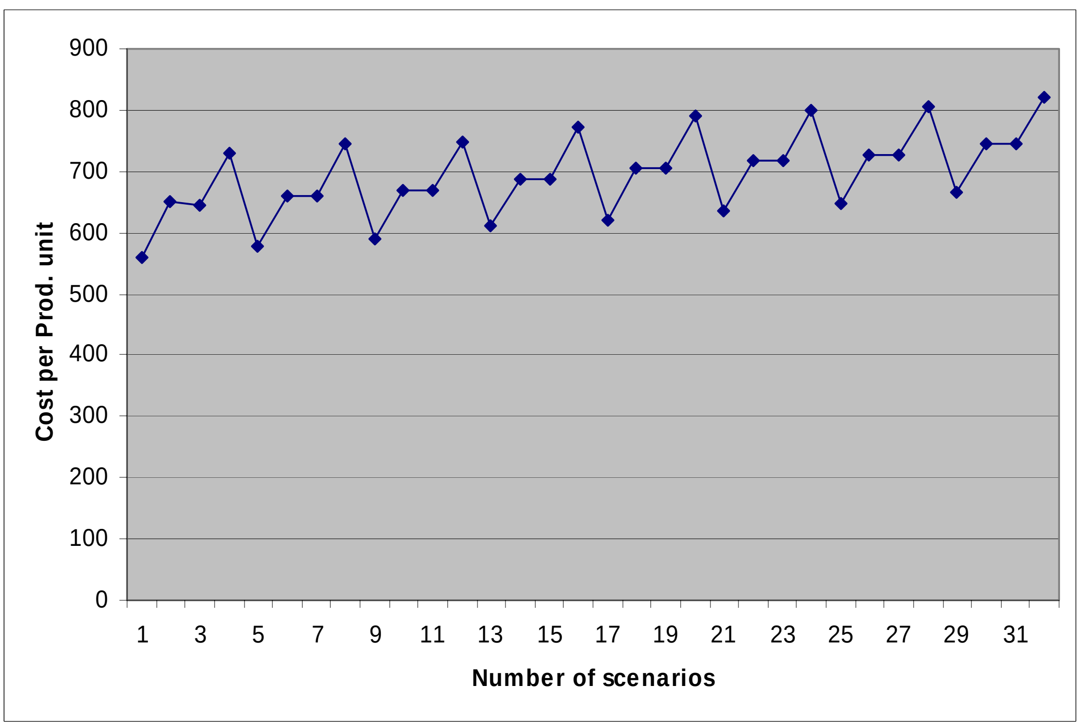


Figure 5-22 Cost per unit (hours) versus scenarios number in FRP bridge decks

5.7.2 Precast concrete deck panels

The sensitivity analysis for Precast concrete deck panels was performed by changing various resources as shown in Table 5-11. A total of 6 out of 9 resources were considered to determine the optimal systems.

Table 5-11 Units of various resources

Systems	Node of no.	Resource	Minimum unit	Maximum unit
FRP bridge deck panel	6	Crane	1	2
	15	Labor	3	6
	18	Pump truck	1	2
	19	Labor	15	20
	22	Bidwell	1	2
	26	Labor	2	4

From the results illustrated in Figure 5-23, the first scenario composed of 1 crane, 3 labors at node number 15, 1 pump truck, 15 labors at node number 19, 1 bidwell, and 2 labors at node number 26 yielded the lowest cost per unit (hours). However, the optimal system was the 361st scenarios that was composed of 2 crane, 4 labors at node number 15, 1 pump truck, 15 labors at node number 19, 1 bidwell, and 2 labors at node number 26 which had the highest cost per productivity units ($53,133.30), almost the lowest cost per unit ($44.80), and productivity per time unit (0.0008cycles/hr). For entire simulation results based on varied resources in Precast concrete decks please refer to appendix G. As shown in Figure 5-24, the cost per productivity unit decreased rapidly in the scenarios 289 ($53,343.83) composed of 2 crane, 3 labors at node number 15, 1 pump truck, 15 labors at node number 19, 1 bidwell, and 2 labors at node number 26. It was evident that the number of cranes was the major factor affecting the productivity. On the other hand, the number of pump truck and bidwell did not seriously affect the productivity. In addition, the number of labors at node number 15 and 19 was another major factor affecting cost per productivity unit. For detailed simulation results of other scenarios please refer to Appendix G.

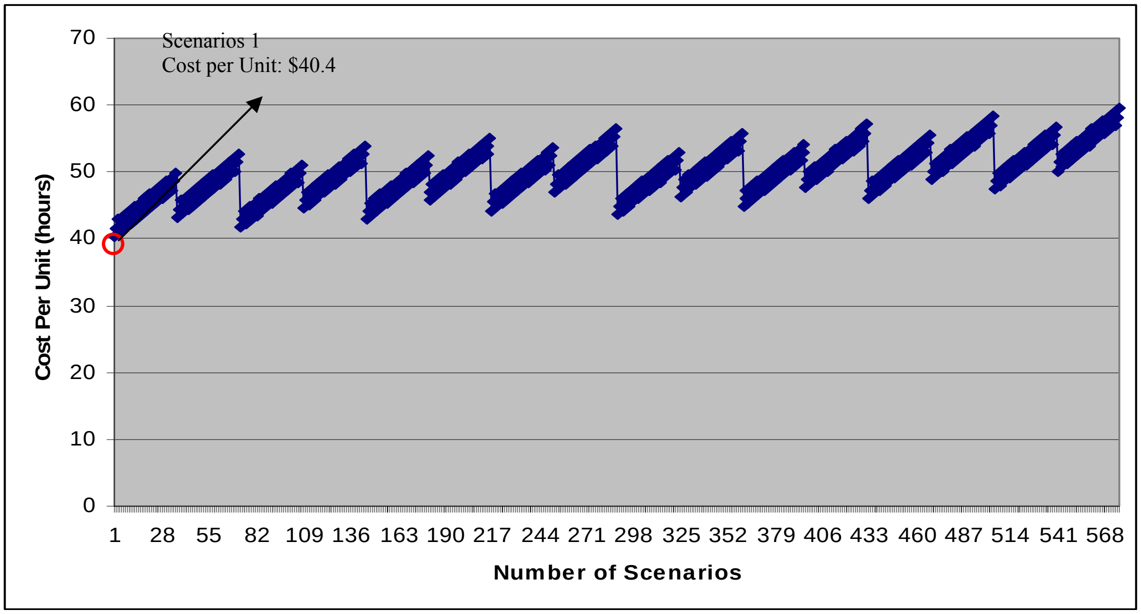


Figure 5-23 Cost per unit versus scenario number in Precast concrete decks

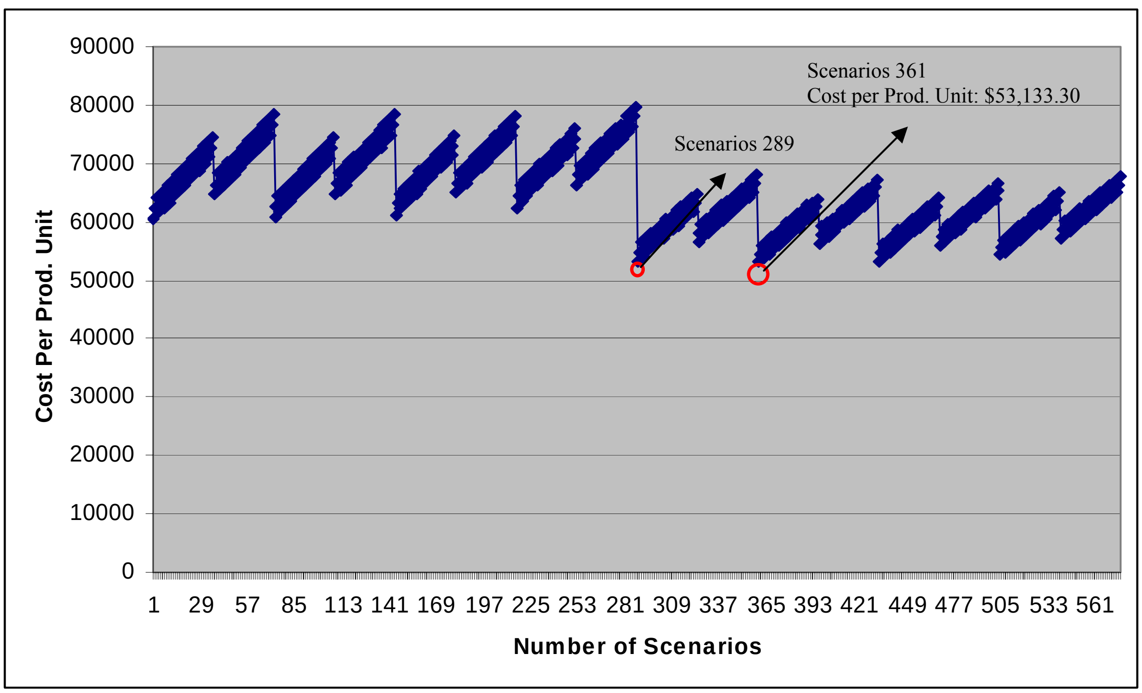


Figure 5-24 Cost per productivity unit versus scenario number in Precast concrete decks

5.8 Comparison of Productivity

As mentioned before, a total square footage of the FRP bridge deck panel project (Fairgrounds Road Bridge) selected for simulation study in this research was 7,400 ft^2 while the square footage for the precast concrete deck panel project was 110,500 ft^2. Converting in terms of ft^2/hr, the productivity of FRP bridge deck panels and Precast concrete decks is 253.82 (ft^2/hr) and 88.4 (ft^2/hr), respectively (Refer to Table 5-12) While the productivity of FRP bridge deck panels decreases, that of Precast concrete deck slightly increases. However, the result was almost similar to simulated result before sensitivity analysis illustrated in Table 5-8. The productivity for FRP bridge deck was almost three times than Precast concrete deck (253.82 / 88.4 = 2.87). Table 5-13 shows the number of optimized resources in both systems.

In the simulation study, the construction costs except for initial material cost were considered to determine the optimal systems in both FRP bridge deck panels and Precast Concrete deck panels. However, as mentioned in Chapter 2, one of main disadvantage of FRP bridge deck panels was higher initial cost compared to a conventional concrete deck. Therefore, this research did not deal with the comparison of unit cost.

Table 5-12 Comparison of productivity in both systems

Optimal Systems	Prod. per unit time	Production/cycle	Productivity (ft^2/hr)
FRP bridge decks	0.0343 (cycles/hr)	7400 ft^2	0.0343*7400 = 253.82 ft^2/hr
Precast concrete decks	0.0008 (cycles/hr)	110,500 ft^2	0.0008*110,500 = 88.4 ft^2/hr

Table 5-13 Optimization of resources in both systems

FRP bridge deck panels	Precast concrete deck panels
(i) One crane and spotter to unload and life panels, (ii) two labors to place and align panels, (iii) one jack to align panels, (iv) one labor to install FRP dowel bars and place FRP splice strips, (v) one labor and stud gun to install shear studs, (vi) two labors and one group pump for grouting, (vii) three labors for guardrail installation.	(i) two labors for laying down Styrofoam fillers on the top flanges of the steel plate girders, (ii) two labors to unload panels, (iii) two cranes to unload and install panels, (iv) three labors to install and align panels, (v) four labors to install epoxy-coated rebar, (vi) one pump truck for pouring concrete, (vii) fifteen labors to pour, cure, and finish concrete, (viii) one bidwell for concrete finishing, and (ix) two labors for guardrail installation.

5.9 References

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CHAPTER 6 Conclusion and Construction Guidelines

6.1 Summary of research

The results of the research are summarized based on (i) Literature review (ii) Preliminary data collection and identification of candidate projects, and (iii) Detailed data collection, analysis and process modeling.

6.1.1 Literature review

The literature review helped in identifying various issues with respect to the construction of FRP composite bridge decks. From the literature review, a fundamental understanding for the FRP composite industry, its unique characteristics, and methodology were summarized in Chapter 2. Their advantages and disadvantages were also summarized in Tables 2-1 and 2-2.

In addition, typical manufacturing processes employed by FRP composite bridge deck manufacturers were introduced; (i) Open molding (Hand lay up process, Chopped laminate process, and Filament winding) and (ii) Closed molding (Resin Transfer Molding (RTM), Resin Infusion Molding, Injection Molding, and Pultrusion). Each of the fabrication processes has its own characteristics that define the type of products to be produced. Several leading FRP composite bridge deck manufacturers were also introduced and their installation procedures were identified: (i) Creative Pultrusion, Inc, (ii) Hardcore Composites Inc., (iii) Kansas Structural Composites, Inc., (iv) Strongwell, and (v) Martin Marietta Composites. In terms of the challenges and technical issues with respect to their application, more efficient manufacturing and effective production methods should be explored and developed to enhance application of FRP composite bridge deck panels in civil infrastructure.

6.1.2 Preliminary Data Collection and Identification of Candidate Projects

Questionnaire survey-I was developed to identify data with regard to (i) standard techniques and material for FRP deck construction, (ii) man-hour requirement, cost, duration, productivity required for individual projects as well as any barriers encountered in installing FRP decks and (iii) constructability, operability, and maintainability of FRP decks. It was sent to the bridge engineers of each State DOT and the county engineers of five candidate projects identified. Responses obtained from the bridge engineers have been analyzed and compiled in Chapter 3. Also, responses from the county engineers have been analyzed and complied in Chapter 4.

Questionnaire-II assisted research team in collecting information with respect to constructability, maintainability, operability, and life cycle cost issues in terms of manufacturers as well as their manufacturing process. Research team visited two manufacturing facilities (Hardcore Composites and Martin Marietta Composites) and interviewed the senior composite engineers at both locations.

(1) Summary of responses from the bridge engineers

Among forty-seven State Departments of Transportation (DOTs) responding to the questionnaire survey-I, only 9 State DOTs have currently used FRP bridge deck panels. The main reasons stated for not using FRP bridge deck panels was due to their higher initial cost and unproved durability as compared to a conventional concrete deck. Other stated reasons include:

- Need more reliable performance data
- Need specification for their design or acceptance by AASHTO
- Lack of supplier and installers
- Need inspection criteria and repair procedures

Based on the results of the questionnaire survey-I, it was determined that only eight percent, among the State DOTs that currently do not use FRP bridge deck panels, have a plan to employ them within next five years. Bridge engineers indicated fast installation and good durability as the major advantage of those panels while the minor advantages include cost saving, less environmental impact, and fewer permits required as compared to conventional bridge deck panels (refer to Figure 3-3). The FRP bridge deck panels have been installed mostly on low volume rural roads (refer to Figure 3-4). The various issues on constructability, operability, and maintainability of FRP bridge deck panels were introduced in Chapter 3 and their conclusions are summarized in the next section.

(2) Summary of responses from the county engineers

In addition to questionnaire survey-I mentioned above, research team visited the construction sites where FRP bridge deck panels were used and interviewed the county engineers responsible for the projects to analyze the installation of advanced modular deck systems and evaluate benefits due to speed and ease of installation. A total of five candidate projects for FRP bridge deck construction were identified in Ohio for on-site data collection and study. The summary of interview and questionnaire survey-I responses obtained from four of the five counties in Ohio is as follows.

1. Criteria used for selecting a bridge for FRP bridge deck panel application
   - Low ADT and ADTT, no skew, and no super-elevation
   - Need a grant for construction because of high initial cost
   - Good shape of existing substructure and concrete beam
2. Unlike the FRP deck panels of other counties, Sintz Road over Rock Run Bridge located in Clark County used fifty ‘Z clips’ instead of grout haunch.
3. The installation of additional FRP deck panels has been scheduled in only one among the four counties within the next five years
4. County engineers indicated the most important advantage of FRP decks as good durability such as fatigue resistance, long service life, and resistance to de-icing salts while they mentioned less environmental impact for the least advantage. The results were similar to the opinion expressed by the bridge engineers (refer to Figure 4-27).
5. Similar to the results of questionnaire-I sent to the bridge engineers, Low Volume Rural was ranked as the most preferred road type for FRP bridge deck panel applications. It was also found that thirty percent of FRP decks have been installed in high volume rural roads. This was one of facts supporting the argument that it is possible for them to be used in bridges with high ADT or ADTT (refer to Figure 4-28).

The various issues on constructability, operability, maintainability of FRP bridge deck panels were introduced in Chapter 4 and their conclusions are summarized in the next section.

(3) Hardcore Composites

Hardcore Composites has finished a total of 28 projects. All of the bridges are designed for L/800 deflection criteria and design load are variable depending on each project. Ohio State DOT has mostly used their product because of Project 100 in Ohio. New York and Delaware were also identified as important customers for their product (Figure 4-35). According to Hardcore Composites, consistent increase in the installation of their product occurred from 1997 to 2000 which peaked in the year 2001, subsequently, a sudden decrease was noticed in the year 2002 (Figure 4-36). Their products have been mostly used on vehicular bridges and only one pedestrian bridge has used their product (Figure 4-37). The “total square footage” of the bridges installed with their product was in the range of 1001 ft^2 to 1500 ft^2. Bridges, whose total square footage ranged from 501 ft^2 to 1000 ft^2, were also an important target for their products (Figure 4-38).

The responses to the questionnaire survey indicated that asphalt worked best for the bridge deck wearing surface. However, polymer concrete was also ranked as one of the preferred materials (Figure 4-39). Hardcore Composites has designed their product to satisfy ASSHTO codes for concrete and steel bridges. They have also offered warranty against their deck for 20 years. However, they do not offer warranty against the following items: acts of God, vandalism, overloading, etc. They have used Vinyl Ester as the type of thermoset resin because of ease in processing and cheap price. Fiberglass was used as the type of fiber since it was less expensive than carbon and aramid and it gives the material properties required in the design. Usually two or three member crews were sent to the job sites for the deck installation. The typical equipment required for the installation of their products are a crane and basic construction tools such as impact wrench and hand tools. The standard size of the crew for installation was two to four member crews. Usually it takes two to five days for installation depending on the complexity of the bridge.

A senior composite engineer of Hardcore Composites indicated that high initial cost, low bidding practices, and lack of confidence or acceptance in the market place were the major obstacles in the application of FRP bridge deck panels. For maintenance practices, they offer a maintenance manual (refer to Appendix D).

(4) Martin Marietta Composites (MMC)

They have 26 bridge decks in service and each is a unique application. They have mostly used 'Bituminous' material for the wearing surface that was usually decided based on the owner's preference. They are willing to consider warranty if required by the owner. With their system, polyester resin and glass fiber typically provides best value. Cranes and jacks are the major equipment required for installing their products. MMC typically recommends a minimum of six member crews for installing their products. Special skill is not required for the crews. MMC expects that it is common to install each of their panels in 30 minutes or less. According to the manufacturer, the effect of fuel, oil, and grease would be negligible as the spill would be typically received by the overlay. In terms of effect of salt and other chemicals, their decks are resistant to corrosion induced by deicing salts.

Like all materials, the owner has responsibility for the maintenance problems. MMC often participates in the first inspection of the bridge and provides assistance in the maintenance activities. So far, they have not experienced the replacement of a partial section in their products.

6.1.3 Detailed Data Collection, Analysis and Process modeling

Construction simulation study was performed to determine the productivity, man-hour requirement and system bottlenecks that were important for understanding the construction process in both FRP bridge deck panels and conventional bridge deck panels. The detailed data required for the simulation studies were collected through questionnaire-III and personal interviews. Among various construction procedures developed by each manufacturer of FRP bridge deck panels, MMC construction procedure was selected for the simulation study. In case of conventional bridge deck, the construction procedure for precast concrete deck panels employed at Cape Girardeau Bridge, Cape Girardeau, Missouri was selected.

FRP bridge deck panels could be installed almost three times faster than precast concrete decks (i.e., 279.375/78.5049 = 3.56 where 279.375 sf^2/hr for FRP bridge deck panels and 78.5049 sf^2/hr represented productivity for precast concrete deck in the sample projects). From the sensitivity analysis (to optimize the performance of a given system by changing the resources or other condition), it was found that the results were almost similar to the above results (i.e., 253.82 / 88.4 = 2.87 where 253.82 sf^2/hr was productivity of FRP bridge deck panels and 88.4 sf^2/hr for the precast concrete deck panels).

The optimal system for FRP bridge deck panels was composed of the following resources: (i) one crane and spotter to unload and lift panels, (ii) two labors to place and align panels, (iii) one jack to align panels, (iv) one labor to install FRP dowel bars and place FRP splice strips, (v) one labor and stud gun to install shear studs, (vi) two labors and one grout pump for grouting and (vii) three labors for guardrail installation.

The optimal system for precast concrete deck panels required (i) two labors for laying down Styrofoam fillers on the top flanges of the steel plate girders, (ii) two labors to unload panels, (iii) two cranes to unload and install panels, (iv) three labors to install and align panels, (v) four labors to install epoxy-coated rebar, (vi) one pump truck for pouring concrete, (vii) fifteen labors to pour, cure, and finish concrete, (viii) one bidwell for concrete finishing, and (ix) two labors for guardrail installation.

6.2 Research Conclusions

6.2.1 Constructability of FRP bridge deck panels

The study invstigated the following issues with regard to constructability of FRP bridge deck panels: (i) Deck structure types, (ii) Construction method, (iii) Wearing surface, (iv) Manufacturing processes, (v) FRP bridge deck cross-section types, (vi) construction specification, (vii) Detailed information on complete project, (viii) Barriers encountered in installing and (ix) Delivery issues. The brief conclusions on these issues are as follows.

(1) Conclusion on responses from the bridge engineers

Concrete cast-in-place and wood or timber were ranked as the deck structure types that have been frequently replaced by FRP bridge deck panels (refer to Figure 3-5). Most manufacturers have developed their own technology to provide the connection between decks and between deck and girder. Until now, the FRP bridge deck panels produced by Martin Marietta Composites, called *DuraSpan*™, have been ranked as the most popular product. The products of Hardcore Composites, Kansas Structural Composites, and Creative Pultrusion have been used by several State DOT (refer to Figure .3-10).

With respect to the material types for wearing surface, bridge engineers indicated that Bituminous and Polymer concrete have been the most preferred materials. Latex Modified Concrete was the least preferred by the State DOTs (refer to Figure 3-15).

Pultrusion has been ranked as the most used manufacturing process. Hand Lay-up and Vacuums Assisted Resin Transfer Modeling (VARTM) processes are also used by many manufacturers (refer to Figure 3-16). Five respondents indicated construction and design barriers as the barriers encountered while installing FRP bridge deck panels whereas, three indicated vendor as the barrier and one of them mentioned labor barriers (refer to Figure 3-19).

Usually, flat bed trucks were used to delivery the FRP panels from factory to the job site and their maximum deliverable sizes were variable depending on project requirements. It took usually a few days to delivery the panels.

(2) Conclusion on responses from the county engineers

With regard to deck structure types, mostly concrete cast-in-place decks have been replaced by FRP decks. Only one of the candidate projects' deck structure type was wood or timber (refer to Figure 4-30).

With respect to the manufacturers, Hardcore composites' product using VARTM manufacturing process has been installed the most in the projects that were studied while Martin Marietta Composites' product (*DuraSpan*^{TM}) was used by two of the candidate projects (refer to Figure 3-30).

Bituminous was ranked as the most important wearing surface material. Only one candidate project employed polymer modified asphalt (refer to Figure 4-31).

In terms of the method for guardrail installation, ‘Guardrail attached to deck’ was a preferred method among the methods used for installing guardrail (refer to Figure 4-32). Design barriers encountered in installing FRP decks were the most important problem. (Figure 4-33).

6.2.2 Operability and Maintainability of FRP bridge deck panels

(1) Conclusion on responses from the bridge engineers

In terms of maintainability issues, deteriorated conventional bridge decks have been mostly replaced by FRP bridge deck panels when their condition rating reached 4 and condition rating 6 or 7 in case of bridge substructure. The durability of wearing surface particularly delamination was indicated most as the highest maintenance problem. Most respondents expected 75 years as service life of FRP bridge deck panels while they mentioned 25 – 50 years as average service life of a concrete bridge deck.

(2) Conclusion on responses from the county engineers

In terms of condition rating of existing bridge structures, deteriorated conventional bridge decks have been replaced by FRP bridge deck panels when their condition rating reached 2 to 4 and condition rating of bridge substructure was 7 (Figure 4-34).

Two counties have not established a specific analysis procedure or method to inspect, maintain and repair the FRP bridge deck panels. One county has performed visual inspection three to four times per years. The county engineer indicated that any repairs to the panels would be undertaken based on discussion with the manufacture. Another county has performed visual inspection once every year. Three counties did not have any plan to monitor the service of FRP bridge deck panels. One of the counties has performed tap test once every year.

Clark county engineers indicated that there were no problems with regard to maintenance and operation after FRP bridge deck panels were installed, however, fire damage was found on the bottom of panels as a probable cause of vandalism.

The maintenance problems commonly generated in other counties were delamination, debonding, and cracking of wearing surface and some minor gaps between the bottom of FRP deck and the concrete beams.

6.3 Construction guidelines for FRP bridge deck panels

Indiana Department of Transportation does not have any definition on the terminology of Construction guidelines. For the purpose of this research, the Construction guidelines of FRP bridge deck panels were defined as the construction procedure, installation methods, and material types used in the construction.

6.3.1 Construction procedure

As indicated in Chapter 2, the construction procedure of FRP bridge deck panels varies from one manufacturer to another. Unlike conventional bridge deck panels such as concrete and steel decks, there are no uniform standards for their construction and thus the manufacturer's own specifications are used. Chapter 2 introduced the construction procedure used by four different manufacturers. However, due to lack of sufficient performance data it is difficult to analyze which construction procedure is more efficient and productive. As mentioned above, the FRP bridge deck panels produced by MMC have been ranked as the most preferred panels based on the questionnaire survey-I conducted for this research. Accordingly, their construction procedure was selected for the simulation study in Chapter 5. In this chapter, their construction procedure including resources required for a certain work task such as equipment and labor were described. The resources required would vary with respect to the project scope. The resources introduced in this section are based on the total square footage of FRP bridge deck panels installed, about 7,500 sf. The construction procedure is as follows:

1. First the panels are unloaded at the job site using a crane.
2. The first panel is installed on the top of girder using a crane and aligned using a jack.
3. The second step is repeated until all panels have been installed. The second and third steps usually require five labors.
4. FRP dowel bars are installed in the lips of the field joints and this step usually requires one labor.
5. FRP splice stripes are installed to ensure a durable and watertight joint, which is usually done by two labors.
6. In order to connect between deck and girder, shear studs are field welded and grout is poured in the cavity. Usually, one labor is required for shear studs and five labors and one grout pump is required for grouting.
7. Finally, guardrail is installed by three labors.

6.3.2 Installation methods

There are two important connection methods for installing FRP bridge deck panels: (i) connection between the decks and (ii) connection of the decks to girders. The two connection methods also vary depending on the manufacturer. Due to lack of performance data, it is not easy to say which connection method is more efficient or inefficient. However, it is possible to say that all manufacturers should improve the construction method of the field joints since delamination, debonding, and cracking of wearing surface have been reported on the field joints of FRP bridge deck panels for all manufacturers according to the results of the questionnaire survey.

6.3.2.1 Connection of deck panels

(1) Martin Marietta Composites (MMC)

Typical panel-to-panel connections are made by using ‘Epoxy adhesive’ in the tongue-and-groove and then the holes are drilled through both sections and FRP dowel bars are placed in the hole. The reason for installing them is to protect the integrity of the bondline while ‘Epoxy adhesive’ cures. Finally, the FRP splice strips are installed over the field joints for durability (refer to Figure 6-1).

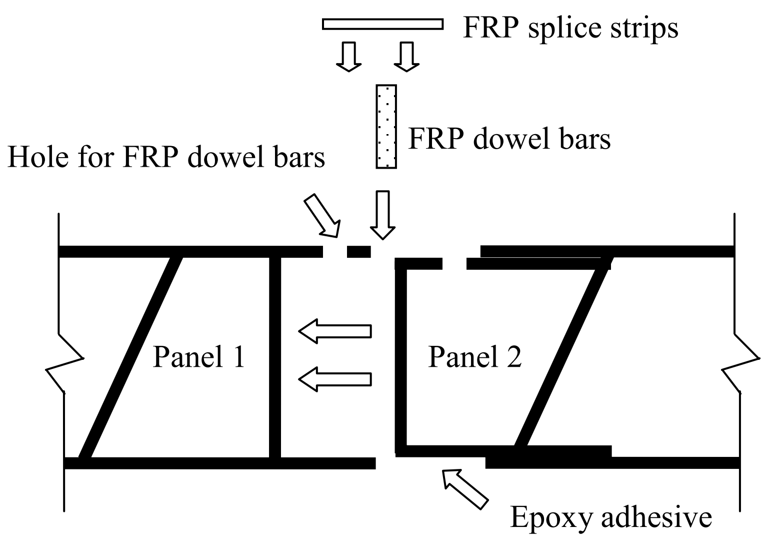


Figure 6-1 MMC joint system

(2) Hardcore Composite Inc. (HCI)

Typically, panel-to-panel connections are made by using 'Epoxy adhesive' in the tongue-and-groove. Finally, FRP splice plates are installed over the field joints for durability (refer to Figure 6-2)

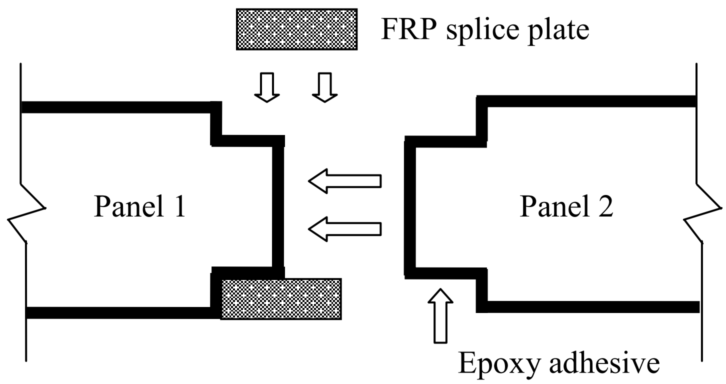


Figure 6-2 HCI joint system

(3) Kansas Structural Composites Inc. (KSCI)

The panel-to-panel connection method is somewhat similar to that of HCI except for using ***bolts and nuts*** instead of FRP splice plates.

(4) Creative Pultrusion Inc. (CPI)

The deck modules are connected with polyurethane adhesive in the tongue-and-groove (refer to Figure 6-3).

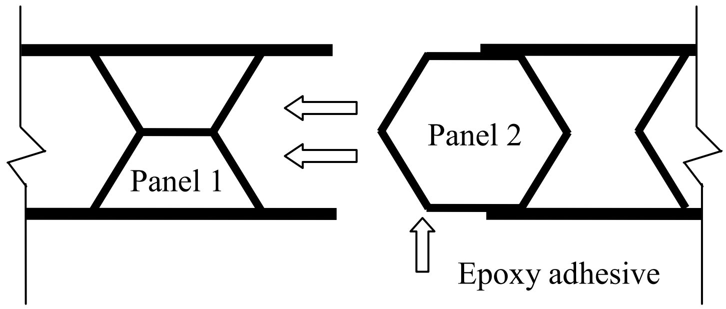


Figure 6-3 CPI joint system

(5) Infrastructure Composites International (ICI)

Pilogrip adhesive is used to connect the male and female ends of adjacent panels together (refer to Figure 6-4)

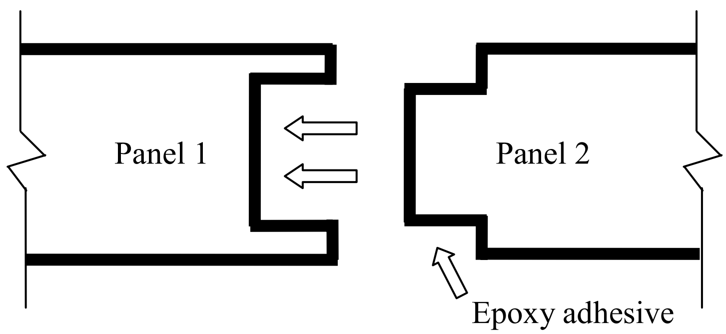


Figure 6-4 ICI joint system

6.3.2.2 Connection of deck-to-girder

(1) Martin Marietta Composites (MMC)

After the decks of MMC are in place, they are connected with the girders by using shear studs (Figure 6-5). As shown in Figure 6-6 (a), holes are cut into the deck at the factory for connection between deck and girder. As shown in Figure 6-6 (c), the shear studs are welded into the girders using a shear stud gun and then non-shrink grout is poured in the cavity as shown in Figure 6-6 (d).

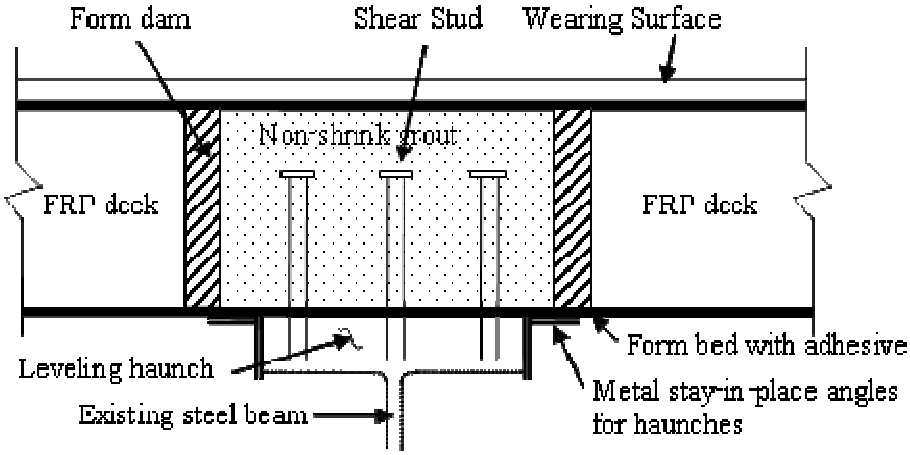
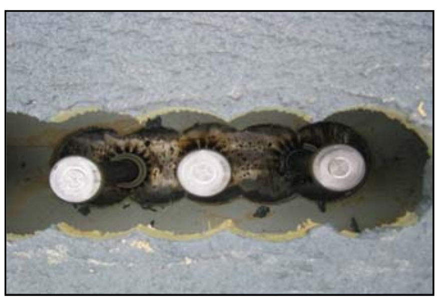


Figure 6-5 MMC deck-to-girder system

(a) Ready to use shear studs

(c) Shear stud gun



(b) After welding shear studs

(d) Non-shrink grouting

(e) After non-shrink grouting

Figure 6-6 Illustration of MMC deck-to-girder system

(2) Hardcore Composite Inc. (HCI)

As shown in Figure 6-7, in the deck-to-girder connection, studs are welded into the concrete beams through predrilled stud holes in each of the panels. Finally, the studs are welded to the steel embedded in deck and to steel plates embedded in the concrete beam. Non-shrink grout is poured in the cavity

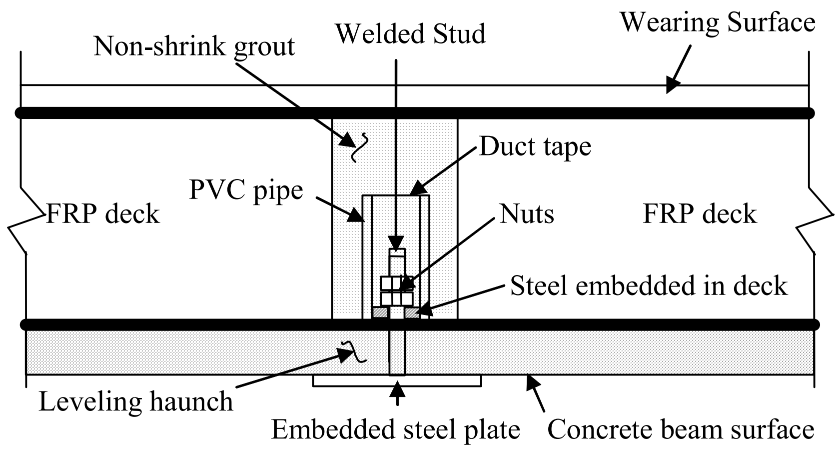


Figure 6-7 HCI deck-to-girder system

(3) Kansas Structural Composites Inc., (KSCI)

To connect deck-to-girder, blind fasteners were used at the joints. 'Blind fasteners' imply that access is needed from only one side of the work piece when they are installed. Polymer concrete is poured to fill the joints.

(4) Creative Pultrusion Inc. (CPI)

Unlike other manufacturers, CPI uses spacer wedges instead of a haunch in order to achieve the desired cross slope. The FRP bridge deck panels are placed on top of the spacer wedges and the shear studs are welded into the existing steel girders through predrilled stud holes in each of the panels. Two cardboard bulkheads are inserted into the deck section in order to make cavity for the grout and then non-shrink grout is poured in the cavity (refer to Figure 6-8)

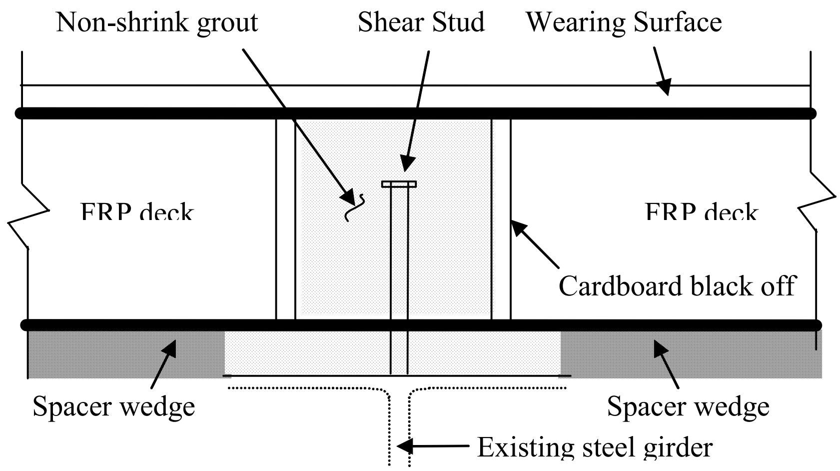


Figure 6-8 CPI deck-to-girder system

(5) Infrastructure Composites International (ICI)

Once the panels are in place, shear studs are welded into the girder flanges through predrilled holes in each of the panels. A plastic cylinder is inserted into the holes in order to make cavity for grout and then non-shrink grout is poured into the cavity.

6.3.3 Material types

With regard to material types used in FRP bridge deck panel construction, only material types for wearing surface were identified in this research. As mentioned earlier in this report, ‘Bituminous’ has been ranked as the most preferred material for wearing surface based on the questionnaire survey-I sent to the bridge engineers and county engineers. In addition, Polymer concrete, epoxy overlay, polymer modified asphalt, and latex modified concrete have been used as materials for the wearing surface. Due to insufficient performance data, it is difficult to say which material type is more efficient or inefficient. Even many State DOTs currently using FRP bridge deck panels have had maintenance problems with the wearing surface. This research found that ‘Bituminous’ material was preferred as wearing surface over other materials including ‘Latex modified concrete’, ‘Epoxy overlay’, and ‘Polymer concrete.’

6.4 Implementation

This research provides construction guidelines for FRP bridge deck panels that could be effectively used by INDOT. These guidelines identify (i) construction sequence, (ii) constructability issues, (iii) maintainability issues, (iv) operability issues, and (v) construction cost issues. Also this research provides information on the state of the art and manufacturing processes currently in use.

The productivity, man-hour requirement, and system bottlenecks for FRP bridge deck construction are determined by construction simulation study. The results obtained from this study could be used by INDOT to improve the productivity of FRP bridge deck construction in the future.

6.5 Recommendations for future research

This research has identified state of the art (research and development) and state of practice of FRP bridge deck panels both in new bridges and in rehabilitation projects. During this research various issues with regard to constructability, operability, maintainability of FRP bridge deck panels were identified. However, in conducting this research, several limitations were also identified.

It was difficult for the research team to compile and analyze data on maintainability, operability, and life cycle cost of FRP bride decks because the new advanced materials have only been applied for highway bridge structures over the last decade in the United States and as such only a few State DOTs have experienced maintenance issues for the FRP bridge deck panels. Thus, it was difficult to prove the advantage of FRP bridge deck panels mentioned in literature review such as cost saving, less expense for maintenance than total replacement and long service life. This is one of the main obstacles in the application of FRP bridge deck panels. In order to enhance their application, the following research should be performed in the future.

1. Innovative modular systems to reduce high initial cost. If the material cost of FRP bridges will not decrease, their application may be limited to bridges of low volume rural types
2. Research on failure of the wearing surface
3. Integration of FRP bridge design, i.e., efficient design and characterization of panel-to-panel joints and attachment of deck-to-girder is required
4. Development of design standards and guidelines
5. Benefit-Cost analysis for economical engineering
6. Develop an analytical model to predict the FRP bridge deterioration over time
7. Develop an analytical model to assess life cycle cost of FRP bridge deck panels.

Appendix A: Questionnaire Survey-I

Joint Transportation Research Program (JTRP)

in Cooperation with the Indiana Department of Transportation
and the Federal Highway Administration

Constructability, Maintainability, and Operability of FIBER REINFORCED POLYMER (FRP) Bridge Deck PANELS

Questionnaire

Conducted by:
Purdue University/Joint Transportation Research Program

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Purpose of Questionnaire

This research is sponsored by the Joint Transportation Research Program in cooperation with the Indiana Department of Transportation and the Federal Highway Administration. This research is being conducted by Prof. Makarand(Mark) Hastak, Ph.D., CCE and Prof. Daniel W. Halpin, Ph.D., School of Civil Engineering, Purdue University.

The purpose of this survey is to collect objective and subjective data with regard to constructability, maintainability, operability of FRP (Fiber Reinforced Polymer) bridge deck panels, and the fabrication, construction methods, quality, safety, man-hour requirements, cost and productivity, as well as the skill level required in order to identify issues related to FRP bridge decks and to develop standard construction guidelines for FRP bridge deck construction.

Your input will assist in the development of a detailed report and research summary that will compile the research findings. The final report will address current state of the art, state of practice of fabrication, and use of FRP bridge decks in addition to development of standard construction guildlines for FRP bridge deck. Please, complete the following information as described. Please take a few minutes to complete the survey. Where numerical data is requested, reasonable estimates and/or ranges are acceptable. Please return the survey by e-mail or regular mail at the address provided on the first page.

Direction

Condition Rate(Table 1) SOURCE: Federal Highway Administration (FHWA). (2002) *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nations Bridges.*

Table 1 General Bridge condition ratings

Code	Description
N	**Not Applicable**
9	**Excellent Condition**
8	**Very Good Condition** – no problems noted
7	**Good Condition –** some minor problems
6	**Satisfactory condition** – structural elements show some minor deterioration
5	**Fair condition** – all primary structural elements are sound but may have minor selection loss, cracking, spalling or scour.
4	**Poor Condition** – advanced section loss, deterioration, spalling or scour
3	**Serious Condition** – loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	**Critical Condition** – advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
1	**"IMMINENT" Failure Condition** – major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.
0	**Failed Condition** – out of service –beyond corrective action.

General Information

Organization: ______________________________

Respondent's name: ______________________________

Position/Title: ______________________________

Address: ______________________________

Tel: ________________ Fax: ________________ E-mail: ________________

Part 1: General information of FRP bridge deck panels

1. Has your DOT used FRP bridge deck panels? ☐ Yes ☐ No

   (If no, go to question 2. If yes, go to question 3.)

2. If your DOT has not installed any FRP bridge deck panels to date, is there any reason? Please specify:

____

____

3. How many FRP bridge deck panels have been scheduled for installation in the near future (within 5 years)? __________

4. Please indicate the following advantages of FRP bridge deck panels by using a scale of priority from 1-5 where 1 = least priority and 5 = top priority.

Advantage	Priority
Increased capacity for live load with possible elimination of weight restrictions	
Fast installation due to modular, prefabricated nature, and reduced traffic delay	
Cost saving, less expense for maintenance than total replacement	
Good durability, fatigue resistance, long service life, resistance to de-icing salts	
Less environmental impact and fewer permits required than replacement	

5. Where does your DOT most commonly use the FRP composite bridge deck panels? (Check all which apply)

- ☐ All multispan precast bridges
- ☐ Interstates
- ☐ High volume urban
- ☐ Low volume urban
- ☐ High volume rural
- ☐ Low volume rural

6. What were the criteria of your state for selecting a bridge for FRP bridge deck panel application?

Please specify: ____

____

____

____

7. How many FRP bridge deck panels have been installed by your state? _________________

No.	Project/Bridge Name	Location	Date Installed	Duration (Day)	# of person	Hours/ person	Manufacturer (Supplier)	Contractor
(1)			___/___/_____					
(2)			___/___/_____					
(3)			___/___/_____					
(4)			___/___/_____					
(5)			___/___/_____					
(6)			___/___/_____					
(7)			___/___/_____					
(8)			___/___/_____					
(9)			___/___/_____					
(10)			___/___/_____					

8. Does your state have any preference in the supplier of FRP bridge deck panels? (Please indicate the reason briefly)

____

____

____

____

Part 2: Constructability of FRP bridge deck panels

9. What deck structure types have been replaced by FRP bridge deck panels? (Check all which apply)

- ☐ Concrete Cast-in-place
- ☐ Concrete Precast Panels
- ☐ Open Grating
- ☐ Closed Grating
- ☐ Steel plate (includes orthotropic)
- ☐ Corrugated steel
- ☐ Aluminum
- ☐ Wood or Timber
- ☐ Other

Please specify:____

10. What type of construction sequence/method is employed for the connection of the FRP bridge deck panels? (Check all which apply)

- ☐ Epoxy adhesive
- ☐ Tongue-and-groove ends
- ☐ Bolts and nuts
- ☐ Epoxy-bonded Diamond-shaped Douglas-fir Inserts
- ☐ Other

Please specify:____

____

11. What type of construction sequence/method is employed for the connection between the FRP bridge deck panels and girder or stringer?

- ☐ Epoxy adhesive
- ☐ Blind Fasteners
- ☐ Other

Please specify:____

12. What is the material of the wearing surface applied for FRP bridge deck panels in your state?

☐ Latex Modified Concrete	☐ Polymer Concrete	☐ Bituminous
☐ Low Slump Concrete	☐ Epoxy Overlay	
☐ Other(specify)		

12-1. What wearing surface aggregate is used?

Please specify: ____

12-2. Who is a manufacturer for the wearing surface?

Please specify: ____

13. Does your state have a specific method of FRP bridge deck panel installation? ☐ Yes ☐ No

If yes, please describe the steps included in your states installation procedure or method?

____

____

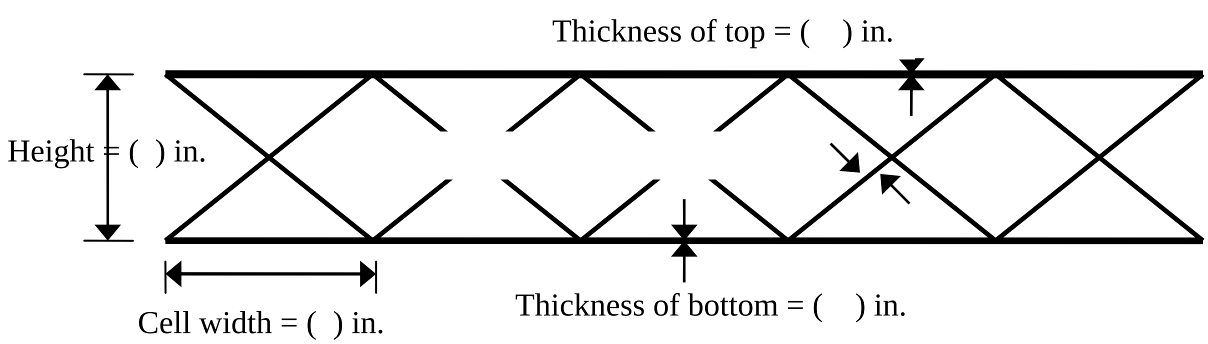
____

14. What kind of manufacturing processes were used to produce the FRP bridge deck panels used by your state? (Check all which apply)

Manufacturing process

- ☐ **Opening Molding**
  - ☐ Hand Lay-up
  - ☐ Chopped Laminate Process
  - ☐ Filament Winding
- ☐ **Closed Molding**
  - ☐ Compression molding
  - ☐ Pultrusion
  - ☐ Reinforced Reaction Injection Molding (RRIM)
  - ☐ Resin Transfer Molding (RTM)
  - ☐ Vacuum Assisted Resin Transfer Molding (VARTM)
  - ☐ Vacuum Bag Molding
  - ☐ Vacuum Infusion Processing
  - ☐ Continuous Lamination
- ☐ Other (specify) ________________________________

15. What is the thickness of top, bottom, and diagonal plates of the FRP bridge cross-section type used in your state? (Please refer to below Figure)



Please specify:

16. What are the construction specifications of FRP bridge deck panels installed by your DOT? (Please specify)

16-1. Standard Specification: ______________________________

____

____

16-2. Specific provision (Warranty from Manufactures): ______________________________

____

____

16-3. Experimental Features (Warranty from FHWA):______________________________

____

____

16-4. Deflection limit, design load (HS25, HS 20, etc.) and other: ______________________________

____

____

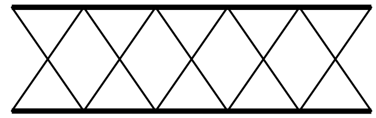
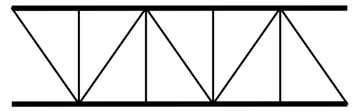
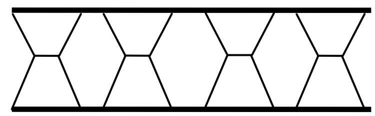
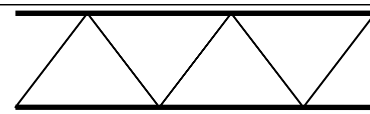
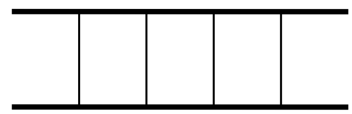
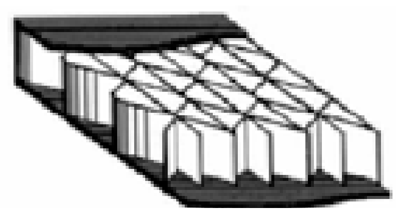
17. Please indicate the size and the number of FRP bridge deck panels.

No.	Project/Bridge Name	# of spans	Size of FPR bridge deck panels (Feet)		Used/span # of FRP bridge deck panels
			Length of panel	Width of panel	
(1)					
(2)					
(3)					
(4)					
(5)					
(6)					
(7)					
(8)					
(9)					
(10)					

18. What kind of barriers were encountered in installing the FRP bridge deck panels? (Check all which apply)

	Barriers	Please specify
☐	Design barriers	
☐	Construction barriers	
☐	Labor barriers	
☐	Vendor barriers	
☐	Other____________________	

19. Please check the cross-section type used in your state. (Check all which apply)

	FRP Bridge deck cross-section type	Shape of the cross-section type
☐	FHWA-Long Beach State Prototype **[X-type]**	
☐	Martin-Marietta **[Box-type]**	
☐	WVU-Creative Pultrusions **[Hexagon-type]**	
☐	Georgia Tech-Atlantic Research Navy Deck **[V-type]**	
☐	Georgia Tech-Strongwell **[Double I-Beams type]**	
☐	Kansas Structural Composites **[Vertical Sine-Wave]**	
☐	Other (Specify): ________________ ______________________________ ______________________________	

20. How does beam spacing affect the slab thickness in FRP bridge deck panels?

Please specify: ____

____

____

21. Please answer the following questions on delivery issues of FRP bridge deck panels.

21-1: What is the method of delivery of FRP bridge deck panels from factory to job site?

Please specify ____

21-2: What are the maximum size of FRP bridge deck panels transported and the cost of transportation?

Please specify ____

21-3: How much time is needed to delivery FRP bridge deck panels from factory to job site?

Please specify ____

22. Where there any other constructability issues not covered above?

Please specify: ____

____

____

____

Part 3: Maintainability and Operability of FRP bridge deck panels

23. What was the condition rate of bridge decks when FRP bridge deck panels were considered for replacing deteriorated bridge decks? (Refer to Table 1)

☐ 9 ☐ 8 ☐ 7 ☐ 6 ☐ 5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐ 0

22-1. What was the condition rate of the substructure when FRP bridge deck panels were selected? (Refer to Table 1)

☐ 9 ☐ 8 ☐ 7 ☐ 6 ☐ 5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐ 0

23. Does your DOT have a specific analysis procedure or method established in order to inspect, maintain, and repair the FPR bridge deck panels after installation? ☐ Yes ☐ No

If yes, please describe what are the steps included in your DOT's analysis procedure or method?

____

____

____

24. In terms of inspection and monitoring the service of FRP bridge deck panels, when are the following (or other) actions taken by your DOT?

[**FA**: age of first application, **FT**: Frequency thereafter (Years)]

Monitoring		Actions	Year
Regular inspection	☐	Tap test	FA: ___ FT:___
	☐	Load Tests	FA: ___ FT:___
	☐	Other(Specify) ______________________________	FA: ___ FT:___
	☐	Other(Specify) ______________________________	FA: ___ FT:___

25. Has your DOT identified any issues/problems with maintenance and operation after the FRP bridge deck panels were installed? ☐ Yes ☐ No

If yes, please describe the issues as well as where and when the issues happened?

____

____

____

26. Please indicate the type and timing of maintenance undertaken for FRP bridge deck panels since construction.

[**FA**: age of first application, **FT**: Frequency thereafter (Years)]

Maintenance	Type of Maintenance	Timing for Maintenance (Years)
Preventive Maintenance		FA: ___ FT:___
		FA: ___ FT:___
Corrective Maintenance		FA: ___ FT:___
		FA: ___ FT:___

27. What is the average service life of FRP bridge deck panels compared to concrete bridge decks in your state? (If historical data, with regard to service life of concrete bridge decks or FRP bridge deck panels, is not available, please answer the following questions based on your experience.)

- Average service life of Concrete Bridge Deck: __________ years
- Expected service life of FRP Composite Bridge Deck: __________ years

Part 4: Life Cycle Cost (LCC) of FRP bridge deck panels

28. What is the expected unit life cycle cost to date of FRP bridge deck panels installed in your DOT (e.g., dollars per square feet): Initial construction cost, user cost, maintenance cost?

No.	Project/ Bridge Name	Life Cycle Cost Items	Unit Cost	Total Cost
(1)		Initial construction Cost		
		Engineering and Fabrication Cost		
		User Cost		
		Maintenance Cost		
		Other ________________________		
		Other________________________		
(2)		Initial construction Cost		
		Engineering and Fabrication Cost		
		User Cost		
		Maintenance Cost		
		Other________________________		
		Other________________________		
(3)		Initial construction Cost		
		Engineering and Fabrication Cost		
		User Cost		
		Maintenance Cost		
		Other________________________		
		Other________________________		

(4)		Initial construction Cost		
		Engineering and Fabrication Cost		
		User Cost		
		Maintenance Cost		
		Other_________________________		
		Other_________________________		
(5)		Initial construction Cost		
		Engineering and Fabrication Cost		
		User Cost		
		Maintenance Cost		
		Other_________________________		
		Other_________________________		
(6)		Initial construction Cost		
		Engineering and Fabrication Cost		
		User Cost		
		Maintenance Cost		
		Other_________________________		
		Other_________________________		

29. Would you be willing to participate in a case study and/or share previous historical data[1] with regard to FRP bridge deck panels with the JTPR research team? Yes ☐ No ☐

If yes, please provide us with the following information:

Contact Name : E-mail :

Telephone : Fax :

Thank you for your input

Please return the finished questionnaire by __________ to:

E-mail hong7@purdue.edu, email: hastak@ecn.purdue.edu

Address Dr. Makarand Hastak, Assistant Professor
(Div. of Constr. Engr. & Mgmt. Purdue University)
Phone: 765-494-2244
Fax: (765) 494-0644

[1] The historical data may include National Inventory databases on FRP bridge deck panels in your DOT

Joint Transportation Research Program (JTRP)

in Cooperation with the Indiana Department of Transportation
and the Federal Highway Administration

Constructability, Maintainability, and Operability of FIBER REINFORCED POLYMER (FRP) Bridge Deck PANELS

Questionnaire # 2

(Manufacturer)

Conducted by:
Purdue University/Joint Transportation Research Program

Please return the finished questionnaire by March. 31. 2004 to:
Dr. Makarand (Mark) Hastak

Project Team

Dr. Makarand Hastak, Assistant Professor
(Div. of Constr. Engr. & Mgmt. Purdue University)
email: hastak@ecn.purdue.edu
Phone: 765-494-2244
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Dr. Daniel W. Haplin. Professor (Head, Div. of Constr. Engr. & Mgmt, Purdue University)
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Fax: (765) 494-0644

TaeHoon Hong, Research Assistant, Ph.D. Candidate
Phone: 765-496-2046, E-mail: hong7@purdue.edu

Purdue University, School of Civil Engineering, 550 Stadium Mall Drive, West Lafayette, Indiana 47907-2051

General Information

Organization: ______________________________

Respondent's name: ______________________________

Position/Title: ______________________________

Address: ______________________________

Tel: __________________Fax: ___________________E-mail: ______________________________

General Information of FRP bridge deck panels

1. What are the advantages of FRP bridge deck panels produced by your company?

Advantage ______________________________

____

____

2. What is the expected service life of FRP bridge deck panels produced by your company?

   (   ) years

3. On what type of bridges are your products being used? (i.e., high volume rural, high volume urban, low volume rural, low volume urban) Please describe the project where your products were used

	Project Name	Location	ADT	Design load	Deflection limit	Bridge types / Volume
(1)						
(2)						
(3)						
(4)						
(5)						

Note: Please use additional sheets as necessary

4. How many FRP bridge deck panels have been scheduled for installation in the near future using your product (within 5 years)? (   )

Constructability Issues of FRP bridge deck panels

5. What is the best material for wearing surface for the FRP bridge deck panels made out of your product?

   (1) Latex modified concrete (2) Polymer Concrete (3) Bituminous (4) Epoxy overlay

   (5) Conventional asphalt (6) Polymer modified asphalt (7) Other ______________________

6. What are the construction specifications for the FRP bridge deck panels installed by your company? Please specify standard specifications

____

____

7. Do you offer warranty with your product? Please specify

____

____

8. What kinds of problems were encountered in installing the FRP bridge deck panels? (i.e., design barriers, construction barriers, labor barriers, vendor barriers, other)

____

____

____

9. What types of thermoset resin have been used in your FRP bridge deck panels?

   (1) Polyester (2) Vinly Ester (3) Epoxy (4) Phenolic (5)Polyurthane (6)Other_______________

Please describe why your company prefers to use these products?

____

10. What kinds of Fibers have been used in your FRP bridge deck panels?

(1) Glass (2) Carbon (3)Aramid (4) Other ____

Please describe why your company prefers to use these products?

____

11. Please explain the railing construction method? (i.e., attached to the deck or cantilevered from the beams)

____

____

12. What types of safety test have been performed on your guardrail design?

____

____

13. What type of equipment is required for the installation of FRP bridge deck panels?

____

____

14. What type of crew is required for the installation of FRP bridge deck panels? (Please specify the skill type, number of labors and equipments involved in the crew)

____

____

____

____

15. What productivity is expected from the crew mentioned above?

____

____

16. Even though FRP composite materials have a lot of advantages over conventional material in construction, the acceptance of their application has been conspicuously slow. What are the major obstacles in their application?

(1) High initial cost (2) Current low bidding practice in the US (3) Lack of material and design specifications (4) other ______________________________

Operability Issues of FRP bridge deck panels bridge deck panels

17. What is the effect of fuel, oil and grease on your FRP bridge deck panels?

____

____

18. What is the procedure of snow removal for your FRP bridge deck panels?

____

____

19. Does it get affected by salt and other chemicals for snow removal?

____

____

20. How do you facilitate water drainage from your installed FRP bridge deck panels?

____

____

Maintainability Issues of FRP bridge deck panels

21. Who has the responsibility for the maintenance problems?

____

____

22. What general maintenance practices do you recommend for your FRP bridge deck panels?

____

____

23. Do you provide assistances in the maintenance activities suggested above?

____

____

24. Does your company have a specific procedure or method established in order to inspect, maintain, and repair the FRP bridge deck panels after installation? ☐ Yes ☐ No

If yes, please describe the procedure or method

____

____

If no, please describe how your company can deal with maintenance problems.

____

____

25. Has your company collected inspection data on completed projects? (i.e., condition rate per year) ☐ Yes ☐ No

If yes, please describe what inspection data are collected by your company.

____

____

26. Has your company identified any issues/problems with regard to maintenance and operation after FRP bridge deck panels were installed? ☐ Yes ☐ No

If so, please describe the issues as well as where and when the issues happened?

(1) Project Name ______________________________
Location ______________________________
Type of maintenance ______________________________
Timing of maintenance ______________________________
Cost of maintenance ______________________________
Method of maintenance ______________________________
Maintained by ______________________________

(2) Project Name ______________________________
Location ______________________________
Type of maintenance ______________________________
Timing of maintenance ______________________________
Cost of maintenance ______________________________
Method of maintenance ______________________________
Maintained by ______________________________

(3) Project Name ______________________________
Location ______________________________
Type of maintenance ______________________________
Timing of maintenance ______________________________
Cost of maintenance ______________________________
Method of maintenance ______________________________
Maintained by ______________________________

(4) Project Name ______________________________
Location ______________________________
Type of maintenance ______________________________
Timing of maintenance ______________________________
Cost of maintenance ______________________________
Method of maintenance ______________________________
Maintained by ______________________________

(5) Project Name ______________________________
Location ______________________________
Type of maintenance ______________________________
Timing of maintenance ______________________________
Cost of maintenance ______________________________

Method of maintenance ____________________
Maintained by ____________________

Note: Please use additional sheets as necessary

27. Has your company experienced the replacement of partial section in FRP bridge deck panels?
☐ Yes ☐ No

If yes, please describe the construction procedure for the replacement.

____

____

Life Cycle Cost Issues of FRP bridge deck panels

28. What is average initial construction cost of FRP bridge deck panels produced by your company? (i.e., dollars per square feet) If there are any other costs related to installing FRP bridge decks such as engineering and fabrication cost, please describe the cost and item

Initial construction cost ____________________
Engineering and Fabrication Cost ____________________
Other cost ____________________

29. Has your company taken any steps (as in research or technology) to reduce high initial cost?
☐ Yes ☐ No

If yes, please describe the research or technology development.

____

____

30. What is currently the best method to reduce high initial cost in your company?

____

____

31. What are the major reasons for high initial cost (i.e., manufacturing, delivery, size etc.)? Please explain

____

____

Appendix C: Questionnaire-III

Joint Transportation Research Program (JTRP)

in Cooperation with the Indiana Department of Transportation
and the Federal Highway Administration

Constructability, Maintainability, and Operability of FIBER REINFORCED POLYMER (FRP) Bridge Deck PANELS

Questionnaire # 3

Conducted by:
Purdue University/Joint Transportation Research Program

Please return the finished questionnaire by __________ to:

Project Team

Dr. Makarand Hastak, Assistant Professor
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Fax: (765) 494-0644

Purdue University, School of Civil Engineering, 550 Stadium Mall Drive, West Lafayette, Indiana 47907-2051

Question Part 1: Duration (Minutes) -How much time did it need to finish a certain work?

1. How long would it take to unload the panels on the job site?
Minimum (   ) minutes Most Likely (   ) minutes Maximum (   ) minutes

2. How long would it take to lift the FRP bridge deck panel (32.6' long 8' wide) by using a crane? (Time for 1 panel)
Minimum (   ) minutes Most Likely (   ) minutes Maximum (   ) minutes

3. How long would it take to place the FRP bridge deck panel (32.6' long 8' wide) into a girder or stringer by using a crane? (Time for 1 panel)
Minimum (   ) minutes Most Likely (   ) minutes Maximum (   ) minutes

4. How long would it take to align the FRP bridge deck panel (32.6’ long 8’ wide) into position by using a jack? (Time for 1 panel)

Minimum (   ) minutes Most Likely (   ) minutes Maximum (   ) minutes

5. How long would it take to install the FRP dowel bars in the lips of the field joints? (Time for entire panels)

Minimum (   ) minutes Most Likely (   ) minutes Maximum (   ) minutes

6. How long would it take to install FRP splice strips in the lips of the field joints? (Time for entire panels)

Minimum (   ) minutes Most Likely (   ) minutes Maximum (   ) minutes

7. How long would it take to install shear studs in order to connect between the deck and girder? (Time for entire panels)

Minimum (   ) minutes Most Likely (   ) minutes Maximum (   ) minutes


8. How long would it take to pour grout in the cavity (refer to above picture) after shear studs are field welded? (Time for entire panels)

Minimum (   ) minutes Most Likely (   ) minutes Maximum (   ) minutes

9. How long would it take to install barrier rails in FRP bridge deck panels? (Time for entire panels)

Minimum (   ) minutes Most Likely (   ) minutes Maximum (   ) minutes

Question Part 2: How many labors were necessary to finish a certain work?

1. How many labors were necessary to finish the placement and alignment of the FRP panels?

2. How many labors were necessary to finish the installment of the FRP dowel bars?

3. How many labors were necessary to finish the placement of the FRP splice strips?

4. How many labors were necessary to finish the connecting between deck and girder?

5. How many labors were necessary to finish the installment of the barrier rails?

6. What major equipments were required?

Appendix D: Hardcore Composites Bridge Inspection and Repair Manual

Inspection and Maintenance Guidelines:

This bridge should be inspected every two years as per normal bridge inspection procedures.

1) Inspect the deck to see if any paint has chipped away and left exposed composite. UV rays from the sun will break down our composites over time. This can be avoided if the deck remains covered with paint.
2) Check the polymer concrete for signs of chipping. Repair with the overlayment that was used for the initial overlayment.
3) Inspect the deck for gouges and degradation that may weaken the properties of the deck.
4) Visual Inspection to see if the Deck has any sagging or other unusual characteristics.
5) The transverse joints in the deck should be inspected every year.
6) The bridge deck should be sounded (tapped with a tap hammer) every inspection. This will detect any delaminations or defects in the deck.

Minor Repairs

There are two sets of minor repairs. One type will be done without consultation with Hardcore and the other repairs will require consultation with Hardcore. The two types of repairs are listed below along with techniques used to fix the damage.

No Consultation

1) Paint Flaking or Chipping off

Problem – paint has been scraped or worn away and left the composite bridge exposed to the outside elements, mainly UV rays from the sun.

Solution

A) Scrap away all loose paint chips and sand the exposed composite with 80 – 150 grit sandpaper to rough up the surface. Do not sand blast the composite as the sand could damage the composite.
B) Clean the area with a solvent.
C) Repaint the area with a Sherwin Williams Tile Clad II Epoxy Paint. Two coats of paint should be applied.

2) Surface Scratches

Problem – Scratches on the surface of the composite can cause future problems if they are not treated correctly. The scratches that are repairable without consulting Hardcore should be less that 1/16-in in depth and less than 24-in in length.

Solution

A) Measure the scratch and make sure that it is less than 1/16-in in depth and less than 24-in. in length.

B) Clean off any dirt or grease that resides in the scratch with a solvent.
C) Fill the crack with a Vinyl Ester Fairing Compound or suitable filler (contact Hardcore for filler recommendation).
D) Sand the VE Compound with medium grit sandpaper.
E) Repaint the portion of the deck with 2 coats of Sherwin Williams Tile Clad II Epoxy Paint.

3) Degradation of the Epoxy Overlayement

Problem – Portions of the overlayment are worn off or chipped off exposing portions of the composite bridge. This can cause problems with point loading on the deck and can cause UV damage to the composite.

Solution
A) Lightly sand the bare composite with medium grit sandpaper.
B) Clean off any dirt or grease that resides in the scratch with a solvent.
C) Fill the area with the original polymer concrete that was first laid on the bridge.

Consultation

1) Blisters

Problem – Small delaminations occur on the bridge due to wear and impacts. The blisters can compromise the structural integrity of the bridge.

Solution
Call Hardcore so that we can evaluate the problem and recommend the proper repair.

2) Delaminations

Problem – Areas of the deck may start to pull apart due to extreme loading conditions. This will weaken the bridge, and immediate repair is necessary.

Solution
Call Hardcore so that we can evaluate the problem and recommend the proper repair.

3) Surface Gouges

Problem – Large surface gouges that are deeper than 1/16” or longer than 24” may cause structural problems in the bridge depending on the location of the gouge. This is due to the fact that the gouge may puncture through one or more face skins.

Solution
Call Hardcore so that we can evaluate the problem and recommend the proper repair.

4) Fire Damage

Problem – If the bridge is exposed to fire for an extended period of time there will be structural damage on the deck. Because the resin burns, some of the bridge will be disintegrated and the bridge structure will be compromised.

Solution
Call Hardcore so that we can evaluate the problem and recommend the proper repair.

5) Deck Punctures/Holes

Problem – Holes and punctures depending on the location on the bridge can degrade the mechanical properties in the bridge. Holes and punctures will be caused by severe point loads.

Solution
Call Hardcore so that we can evaluate the problem and recommend the proper repair.

Major repairs

Any type of damage that occurs to one of our bridge can usually be repaired. If any large-scale damage occurs to the deck call Hardcore so that the damage can be evaluated. It is impossible to determine what types of defects would require replacement of the bridge until the extent of that damage has been analyzed by Hardcore.

Appendix E: Input Files for FRP Bridge Deck Panels

```
NAME FRP BRIDGE DECK PANEL INSTALLATION(GREENE COUNTY) LENGTH
2000000 CYCLE 300
NETWORK INPUT
1 QUE 'PANEL ARRIVAL'
2 QUE 'CRANE IDLE'
3 QUE 'SPOTTER AVAIL'
4 COM 'PANEL BEING UNLOADED' SET 4 PRE 1 2 3 FOL 2 3 5
5 QUE 'PANEL AVAIL' GEN 24
6 COM 'LIFT' SET 6 PRE 2 3 5 FOL 2 3 7
7 QUE 'WAIT PLACE'
8 QUE 'LABOR IDLE'
9 COM 'PANEL PLACE' SET 9 PRE 7 8 FOL 8 10
10 QUE 'WAIT TO ALIGN'
11 QUE 'JACK IDLE'
12 COM 'ALIGN PANELS IN POSITION' SET 12 PRE 8 10 11 FOL 8 11 13
13 FUN CON 24 FOL 14
14 QUE 'WAIT TO INSTALL DOWEL BARS'
15 QUE 'LABOR'
16 COM 'FRP DOWEL BARS INSTALLATION' SET 16 PRE 14 15 FOL 15 17
17 QUE 'WAIT TO STRIP'
18 COM 'FRP SPLICE STRIPS PLACEMENT' SET 18 PRE 15 17 FOL 15 19
19 QUE 'WAIT SHEAR CONNECTOR'
20 QUE 'LABOR IDLE'
21 QUE 'STUD GUN IDEL'
22 COM 'SHEAR STUDS INSTALLATION' SET 22 PRE 19 20 21 FOL 20 21 23
23 QUE 'WAIT TO GROUT'
24 QUE 'GROUT PUMP IDLE'
25 COM 'GROUTING' SET 25 PRE 8 23 24 FOL 8 24 26
26 QUE 'WAIT RAIL INSTALL'
27 QUE 'LABOR IDLE'
28 COM 'RAIL INSTALL' SET 28 PRE 26 27 FOL 27 29
29 FUN COU FOL 1 QUA 1
DURATION INPUT
SET 4 TRI 0.17 0.25 0.3
SET 6 TRI 0.03 0.07 0.1
SET 9 TRI 0.17 0.25 0.3
SET 12 TRI 0.17 0.33 0.42
SET 16 TRI 0.02 0.03 0.08
SET 18 TRI 0.75 1 1.5
SET 22 TRI 0.5 0.75 1
SET 25 TRI 0.5 0.75 1
SET 28 TRI 15 16 17
RESOURCE INPUT
```

```
1 'PANEL' AT 1 FIXED 1
1 'CRANE' AT 2 FIXED 125
1 'SPOTTER' AT 3 FIXED 75
5 'LABOR' AT 8 FIXED 75
1 'JACK' AT 11 FIXED 1
2 'LABOR' AT 15 FIXED 75
1 'LABOR' AT 20 FIXED 75
1 'STUD GUN' AT 21 FIXED 175
1 'Grout pump' AT 24 FIXED 175
3 'LABOR' AT 27 FIXED 75
ENDDATA
```

Appendix F: Input Files for Precast Concrete Deck Panels

```
NAME PRECAST Concrete BRIDGE DECK PANEL INSTALLATION LENGTH 9000000
CYCLE 20
NETWORK INPUT
1 QUE 'READY TO INSTALL DECK'
2 QUE 'LABOR IDLE'
3 COM 'LAY DOWN' SET 3 PRE 1 2 FOL 2 4
4 QUE 'WAIT TO UNLOAD'
5 QUE 'LABOR IDLE'
6 QUE 'CRANE IDEL'
7 COM 'PANELS BEING UNLOADED' SET 7 PRE 4 5 6 FOL 5 6 8
8 QUE 'WAIT TO 10' GEN 1404
9 QUE 'LABOR IDLE'
10 COM 'INSTALL PANELS' SET 10 PRE 6 8 9 FOL 6 9 11
11 QUE 'WAIT TO ALIGN'
12 COM 'ALIGN PANELS' SET 12 PRE 9 11 FOL 9 13
13 FUN CON 1404 FOL 14
14 QUE 'WAIT TO INSTALL' GEN 15
15 QUE 'LABOR IDEL'
16 COM 'INSTALL REBAR' SET 16 PRE 14 15 FOL 15 17
17 QUE 'CONCRETE AVAIL'
18 QUE 'PUMP TRUCK AVAIL'
19 QUE 'LABOR IDEL'
20 COM 'POUR CONCRETE' SET 20 PRE 17 18 19 FOL 18 19 21
21 QUE 'WAIT TO CURE&FINISH'
22 QUE 'BIDWELL AVAIL'
23 COM 'FINISHING & CURING' SET 23 PRE 19 21 22 FOL 19 22 24
24 FUN CON 15 FOL 25
25 QUE 'WAIT TO INSTALL'
26 QUE 'LABOR IDLE'
27 COM 'INSTALL BARRIER RAIL' SET 27 PRE 22 25 26 FOL 22 26 28
28 FUN COU FOL 1 QUA 1
DURATION INPUT
SET 3 408
SET 7 TRI 4 6 8
SET 10 TRI 0.25 0.5 1
SET 12 TRI 0.25 0.5 1
SET 16 40
SET 20 TRI 5 6 7
SET 23 TRI 1 2 3
SET 27 TRI 30 45 60
RESOURCE INPUT
```

```
1 'READY TO INSTALL DECK' AT 1 FIXED 1
2 'LABOR IDLE' AT 2 FIXED 75
2 'LABOR IDLE' AT 5 FIXED 75
1 'CRANE' AT 6 FIXED 187
3 'LABOR' AT 9 FIXED 75
6 'LABOR' AT 15 FIXED 75
1 'PUMP TRUCK' AT 18 FIXED 170
20 'LABOR' AT 19 FIXED 75
1 'BIDWELL' AT 22 FIXED 38.50
4 'LABOR' AT 26 FIXED 75
ENDDATA
```

Appendix G: Simulation Results based on varied resources in Precast Concrete Decks

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
1	1	3	1	15	1	2	0.0007	40.4004	60537.50
2	1	3	1	15	1	3	0.0007	41.6229	62412.50
3	1	3	1	15	1	4	0.0007	42.9331	64030.35
4	1	3	1	15	2	2	0.0007	41.066	61623.00
5	1	3	1	15	2	3	0.0007	42.2654	63375.00
6	1	3	1	15	2	4	0.0007	43.5261	65119.50
7	1	3	1	16	1	2	0.0007	41.6487	62412.50
8	1	3	1	16	1	3	0.0007	42.9103	64287.50
9	1	3	1	16	1	4	0.0007	44.1346	66162.50
10	1	3	1	16	2	2	0.0007	42.2734	63248.25
11	1	3	1	16	2	3	0.0007	43.5633	65250.00
12	1	3	1	16	2	4	0.0007	44.7691	66856.50
13	1	3	1	17	1	2	0.0007	42.8589	64416.08
14	1	3	1	17	1	3	0.0007	44.1439	66162.50
15	1	3	1	17	1	4	0.0007	45.419	68037.50
16	1	3	1	17	2	2	0.0007	43.5831	65380.50
17	1	3	1	17	2	3	0.0007	44.8172	66990.75
18	1	3	1	17	2	4	0.0007	46.0338	69000.00
19	1	3	1	18	1	2	0.0007	44.1372	66162.50
20	1	3	1	18	1	3	0.0007	45.4371	68037.50
21	1	3	1	18	1	4	0.0007	46.6919	70052.33
22	1	3	1	18	2	2	0.0007	44.8158	67259.25
23	1	3	1	18	2	3	0.0007	46.071	69138.00
24	1	3	1	18	2	4	0.0007	47.2869	70875.00
25	1	3	1	19	1	2	0.0007	45.4418	68037.50
26	1	3	1	19	1	3	0.0007	46.6757	70052.33
27	1	3	1	19	1	4	0.0007	47.8644	71643.93
28	1	3	1	19	2	2	0.0007	46.0186	68862.00
29	1	3	1	19	2	3	0.0007	47.2872	70733.25
30	1	3	1	19	2	4	0.0007	48.5758	72895.50
31	1	3	1	20	1	2	0.0007	46.6543	69912.50
32	1	3	1	20	1	3	0.0007	47.9515	71931.08
33	1	3	1	20	1	4	0.0007	49.109	73515.18
34	1	3	1	20	2	2	0.0007	47.2706	71016.75
35	1	3	1	20	2	3	0.0007	48.588	72750.00
36	1	3	1	20	2	4	0.0007	49.7554	74625.00
37	1	3	2	15	1	2	0.0007	43.2733	64787.50
38	1	3	2	15	1	3	0.0007	44.4838	66262.53
39	1	3	2	15	1	4	0.0007	45.744	68263.35

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
40	1	3	2	15	2	2	0.0007	43.8525	65618.50
41	1	3	2	15	2	3	0.0007	45.095	67489.75
42	1	3	2	15	2	4	0.0007	46.3764	69222.00
43	1	3	2	16	1	2	0.0007	44.4905	66395.85
44	1	3	2	16	1	3	0.0007	45.7092	68126.28
45	1	3	2	16	1	4	0.0007	46.9896	70271.68
46	1	3	2	16	2	2	0.0007	45.1402	67219.25
47	1	3	2	16	2	3	0.0007	46.3923	69222.00
48	1	3	2	16	2	4	0.0007	47.5993	70946.75
49	1	3	2	17	1	2	0.0007	45.7006	68126.28
50	1	3	2	17	1	3	0.0007	47.021	70130.85
51	1	3	2	17	1	4	0.0007	48.1947	71853.78
52	1	3	2	17	2	2	0.0007	46.3827	69222.00
53	1	3	2	17	2	3	0.0007	47.6732	71375.00
54	1	3	2	17	2	4	0.0007	48.9099	72810.50
55	1	3	2	18	1	2	0.0007	46.9972	70130.85
56	1	3	2	18	1	3	0.0007	48.2272	72142.93
57	1	3	2	18	1	4	0.0007	49.5406	73865.85
58	1	3	2	18	2	2	0.0007	47.6119	71232.25
59	1	3	2	18	2	3	0.0007	48.8373	72810.50
60	1	3	2	18	2	4	0.0007	50.1553	74824.50
61	1	3	2	19	1	2	0.0007	48.2515	71998.35
62	1	3	2	19	1	3	0.0007	49.4809	73865.85
63	1	3	2	19	1	4	0.0007	50.7558	75733.35
64	1	3	2	19	2	2	0.0007	48.891	72810.50
65	1	3	2	19	2	3	0.0007	50.1423	74974.75
66	1	3	2	19	2	4	0.0007	51.4364	76692.00
67	1	3	2	20	1	2	0.0007	49.4836	73569.20
68	1	3	2	20	1	3	0.0007	50.7241	75733.35
69	1	3	2	20	1	4	0.0007	51.9845	77445.03
70	1	3	2	20	2	2	0.0007	50.088	74674.25
71	1	3	2	20	2	3	0.0007	51.3744	76692.00
72	1	3	2	20	2	4	0.0007	52.6464	78401.75
73	1	4	1	15	1	2	0.0007	41.6749	60789.78
74	1	4	1	15	1	3	0.0007	42.8827	62487.45
75	1	4	1	15	1	4	0.0007	44.1412	64442.28
76	1	4	1	15	2	2	0.0007	42.2731	61600.50
77	1	4	1	15	2	3	0.0007	43.5035	63423.00
78	1	4	1	15	2	4	0.0007	44.7926	65379.75
79	1	4	1	16	1	2	0.0007	42.8813	62487.45
80	1	4	1	16	1	3	0.0007	44.1411	64442.28
81	1	4	1	16	1	4	0.0007	45.4183	66268.53
82	1	4	1	16	2	2	0.0007	43.5395	63423.00
83	1	4	1	16	2	3	0.0007	44.7539	65111.25
84	1	4	1	16	2	4	0.0007	46.0661	67206.00

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
85	1	4	1	17	1	2	0.0007	44.1311	64309.95
86	1	4	1	17	1	3	0.0007	45.4444	66404.60
87	1	4	1	17	1	4	0.0007	46.6215	67954.95
88	1	4	1	17	2	2	0.0007	44.8221	65379.75
89	1	4	1	17	2	3	0.0007	46.0568	67206.00
90	1	4	1	17	2	4	0.0007	47.3012	69032.25
91	1	4	1	18	1	2	0.0007	45.3598	66132.45
92	1	4	1	18	1	3	0.0007	46.6106	67954.95
93	1	4	1	18	1	4	0.0007	47.8626	69921.03
94	1	4	1	18	2	2	0.0007	46.0756	67206.00
95	1	4	1	18	2	3	0.0007	47.3031	69032.25
96	1	4	1	18	2	4	0.0007	48.5141	70858.50
97	1	4	1	19	1	2	0.0007	46.6655	67954.95
98	1	4	1	19	1	3	0.0007	47.9559	70064.60
99	1	4	1	19	1	4	0.0007	49.205	71894.60
100	1	4	1	19	2	2	0.0007	47.2549	68890.50
101	1	4	1	19	2	3	0.0007	48.5998	70858.50
102	1	4	1	19	2	4	0.0007	49.8124	72684.75
103	1	4	1	20	1	2	0.0007	47.9238	69921.03
104	1	4	1	20	1	3	0.0007	49.1568	71599.95
105	1	4	1	20	1	4	0.0007	50.4054	73573.53
106	1	4	1	20	2	2	0.0007	48.5063	70858.50
107	1	4	1	20	2	3	0.0007	49.835	72535.50
108	1	4	1	20	2	4	0.0007	51.0662	74358.00
109	1	4	2	15	1	2	0.0007	44.4959	64662.63
110	1	4	2	15	1	3	0.0007	45.7527	66481.38
111	1	4	2	15	1	4	0.0007	47.0329	68300.13
112	1	4	2	15	2	2	0.0007	45.1231	65461.00
113	1	4	2	15	2	3	0.0007	46.3712	67276.00
114	1	4	2	15	2	4	0.0007	47.6805	69233.75
115	1	4	2	16	1	2	0.0007	45.7246	66344.30
116	1	4	2	16	1	3	0.0007	46.9504	68300.13
117	1	4	2	16	1	4	0.0007	48.22	70118.88
118	1	4	2	16	2	2	0.0007	46.4234	67415.00
119	1	4	2	16	2	3	0.0007	47.6438	69233.75
120	1	4	2	16	2	4	0.0007	48.8576	71052.50
121	1	4	2	17	1	2	0.0007	47.0349	68440.95
122	1	4	2	17	1	3	0.0007	48.2044	70118.88
123	1	4	2	17	1	4	0.0007	49.5223	71789.30
124	1	4	2	17	2	2	0.0007	47.5886	69233.75
125	1	4	2	17	2	3	0.0007	48.8837	71052.50
126	1	4	2	17	2	4	0.0007	50.1185	72721.00
127	1	4	2	18	1	2	0.0007	48.2716	70118.88
128	1	4	2	18	1	3	0.0007	49.54	71937.63

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
129	1	4	2	18	1	4	0.0007	50.6949	73452.23
130	1	4	2	18	2	2	0.0007	48.8674	71052.50
131	1	4	2	18	2	3	0.0007	50.0964	72871.25
132	1	4	2	18	2	4	0.0007	51.3642	74536.00
133	1	4	2	19	1	2	0.0007	49.5246	72085.95
134	1	4	2	19	1	3	0.0007	50.7141	73604.30
135	1	4	2	19	1	4	0.0007	52.0069	75575.13
136	1	4	2	19	2	2	0.0007	50.1614	72721.00
137	1	4	2	19	2	3	0.0007	51.3342	74536.00
138	1	4	2	19	2	4	0.0007	52.6588	76666.50
139	1	4	2	20	1	2	0.0007	50.7447	73908.45
140	1	4	2	20	1	3	0.0007	52.0397	75575.13
141	1	4	2	20	1	4	0.0007	53.2316	77393.88
142	1	4	2	20	2	2	0.0007	51.3613	74690.00
143	1	4	2	20	2	3	0.0007	52.6371	76508.75
144	1	4	2	20	2	4	0.0007	53.9331	78327.50
145	1	5	1	15	1	2	0.0007	42.8614	61201.70
146	1	5	1	15	1	3	0.0007	44.1958	63251.35
147	1	5	1	15	1	4	0.0007	45.3832	64907.78
148	1	5	1	15	2	2	0.0007	43.556	62248.50
149	1	5	1	15	2	3	0.0007	44.7608	64171.50
150	1	5	1	15	2	4	0.0007	46.0201	65826.00
151	1	5	1	16	1	2	0.0007	44.1123	63119.03
152	1	5	1	16	1	3	0.0007	45.4281	64907.78
153	1	5	1	16	1	4	0.0007	46.6799	66696.53
154	1	5	1	16	2	2	0.0007	44.7801	64305.75
155	1	5	1	16	2	3	0.0007	46.0678	65688.00
156	1	5	1	16	2	4	0.0007	47.2648	67614.75
157	1	5	1	17	1	2	0.0007	45.4334	64907.78
158	1	5	1	17	1	3	0.0007	46.6888	66696.53
159	1	5	1	17	1	4	0.0007	47.8892	68628.85
160	1	5	1	17	2	2	0.0007	46.0523	65826.00
161	1	5	1	17	2	3	0.0007	47.2974	67614.75
162	1	5	1	17	2	4	0.0007	48.5215	69403.50
163	1	5	1	18	1	2	0.0007	46.7005	66836.35
164	1	5	1	18	1	3	0.0007	47.8755	68341.70
165	1	5	1	18	1	4	0.0007	49.1541	70274.03
166	1	5	1	18	2	2	0.0007	47.3151	67756.50
167	1	5	1	18	2	3	0.0007	48.5545	69403.50
168	1	5	1	18	2	4	0.0007	49.7637	71341.50
169	1	5	1	19	1	2	0.0007	47.8829	68628.85
170	1	5	1	19	1	3	0.0007	49.1988	70421.35
171	1	5	1	19	1	4	0.0007	50.3831	72062.78
172	1	5	1	19	2	2	0.0007	48.511	69403.50

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
173	1	5	1	19	2	3	0.0007	49.796	71341.50
174	1	5	1	19	2	4	0.0007	51.0946	72981.00
175	1	5	1	20	1	2	0.0007	49.198	70274.03
176	1	5	1	20	1	3	0.0007	50.3974	71911.70
177	1	5	1	20	1	4	0.0007	51.651	73851.53
178	1	5	1	20	2	2	0.0007	49.7679	71341.50
179	1	5	1	20	2	3	0.0007	51.0602	72981.00
180	1	5	1	20	2	4	0.0007	52.3484	74926.50
181	1	5	2	15	1	2	0.0007	45.7552	64973.55
182	1	5	2	15	1	3	0.0007	46.9483	66610.23
183	1	5	2	15	1	4	0.0007	48.2353	68528.55
184	1	5	2	15	2	2	0.0007	46.3541	65886.00
185	1	5	2	15	2	3	0.0007	47.6435	67520.75
186	1	5	2	15	2	4	0.0007	48.8364	69294.50
187	1	5	2	16	1	2	0.0007	46.943	66469.40
188	1	5	2	16	1	3	0.0007	48.2377	68383.98
189	1	5	2	16	1	4	0.0007	49.4834	70306.05
190	1	5	2	16	2	2	0.0007	47.6742	67663.50
191	1	5	2	16	2	3	0.0007	48.8941	69441.00
192	1	5	2	16	2	4	0.0007	50.1307	71218.50
193	1	5	2	17	1	2	0.0007	48.2544	68673.13
194	1	5	2	17	1	3	0.0007	49.5214	70306.05
195	1	5	2	17	1	4	0.0007	50.7292	72083.55
196	1	5	2	17	2	2	0.0007	48.8981	69441.00
197	1	5	2	17	2	3	0.0007	50.0912	70918.00
198	1	5	2	17	2	4	0.0007	51.4403	72996.00
199	1	5	2	18	1	2	0.0007	49.5123	70157.73
200	1	5	2	18	1	3	0.0007	50.7785	72083.55
201	1	5	2	18	1	4	0.0007	51.9565	73705.23
202	1	5	2	18	2	2	0.0007	50.1056	71068.25
203	1	5	2	18	2	3	0.0007	51.3838	72996.00
204	1	5	2	18	2	4	0.0007	52.622	74773.50
205	1	5	2	19	1	2	0.0007	50.7325	72083.55
206	1	5	2	19	1	3	0.0007	52.0022	73705.23
207	1	5	2	19	1	4	0.0007	53.207	75319.40
208	1	5	2	19	2	2	0.0007	51.4141	72842.00
209	1	5	2	19	2	3	0.0007	52.6544	74931.25
210	1	5	2	19	2	4	0.0007	53.9184	76389.50
211	1	5	2	20	1	2	0.0007	51.9965	73705.23
212	1	5	2	20	1	3	0.0007	53.2272	75478.98
213	1	5	2	20	1	4	0.0007	54.483	77252.73
214	1	5	2	20	2	2	0.0007	52.6833	74773.50
215	1	5	2	20	2	3	0.0007	53.8869	76389.50
216	1	5	2	20	2	4	0.0007	55.0937	77998.00

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
217	1	6	1	15	1	2	0.0007	44.1236	62457.40
218	1	6	1	15	1	3	0.0007	45.4414	64499.55
219	1	6	1	15	1	4	0.0007	46.6953	66277.05
220	1	6	1	15	2	2	0.0007	44.8067	63500.25
221	1	6	1	15	2	3	0.0007	46.0544	65274.00
222	1	6	1	15	2	4	0.0007	47.2524	67189.50
223	1	6	1	16	1	2	0.0007	45.3637	64363.48
224	1	6	1	16	1	3	0.0007	46.7046	66277.05
225	1	6	1	16	1	4	0.0007	47.9104	68054.55
226	1	6	1	16	2	2	0.0007	46.0904	65550.00
227	1	6	1	16	2	3	0.0007	47.3166	67189.50
228	1	6	1	16	2	4	0.0007	48.6013	68967.00
229	1	6	1	17	1	2	0.0007	46.673	66277.05
230	1	6	1	17	1	3	0.0007	47.8893	67767.40
231	1	6	1	17	1	4	0.0007	49.1405	69832.05
232	1	6	1	17	2	2	0.0007	47.2771	67189.50
233	1	6	1	17	2	3	0.0007	48.5667	68967.00
234	1	6	1	17	2	4	0.0007	49.8292	70595.25
235	1	6	1	18	1	2	0.0007	47.9523	68054.55
236	1	6	1	18	1	3	0.0007	49.1489	69832.05
237	1	6	1	18	1	4	0.0007	50.4075	71458.48
238	1	6	1	18	2	2	0.0007	48.504	68821.50
239	1	6	1	18	2	3	0.0007	49.8007	70595.25
240	1	6	1	18	2	4	0.0007	51.1023	72675.00
241	1	6	1	19	1	2	0.0007	49.1137	69684.73
242	1	6	1	19	1	3	0.0007	50.3599	71458.48
243	1	6	1	19	1	4	0.0007	51.7126	73387.05
244	1	6	1	19	2	2	0.0007	49.8079	70893.75
245	1	6	1	19	2	3	0.0007	51.0538	72369.00
246	1	6	1	19	2	4	0.0007	52.2919	73986.00
247	1	6	1	20	1	2	0.0007	50.3592	71458.48
248	1	6	1	20	1	3	0.0007	51.6184	73232.23
249	1	6	1	20	1	4	0.0007	52.9359	75164.55
250	1	6	1	20	2	2	0.0007	51.053	72522.00
251	1	6	1	20	2	3	0.0007	52.3406	74299.50
252	1	6	1	20	2	4	0.0007	53.5203	76077.00
253	1	6	2	15	1	2	0.0007	47.0215	66328.58
254	1	6	2	15	1	3	0.0007	48.2483	68239.40
255	1	6	2	15	1	4	0.0007	49.498	69712.75
256	1	6	2	15	2	2	0.0007	47.6536	67378.00
257	1	6	2	15	2	3	0.0007	48.8544	68855.00
258	1	6	2	15	2	4	0.0007	50.138	70617.50
259	1	6	2	16	1	2	0.0007	48.2474	68094.83
260	1	6	2	16	1	3	0.0007	49.5043	70009.40

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
261	1	6	2	16	1	4	0.0007	50.7317	71627.33
262	1	6	2	16	2	2	0.0007	48.9265	69148.00
263	1	6	2	16	2	3	0.0007	50.1775	70918.00
264	1	6	2	16	2	4	0.0007	51.3486	72534.00
265	1	6	2	17	1	2	0.0007	49.4568	70009.40
266	1	6	2	17	1	3	0.0007	50.7505	71779.40
267	1	6	2	17	1	4	0.0007	51.9771	73549.40
268	1	6	2	17	2	2	0.0007	50.1279	70767.75
269	1	6	2	17	2	3	0.0007	51.3987	72534.00
270	1	6	2	17	2	4	0.0007	52.664	74300.25
271	1	6	2	18	1	2	0.0007	50.7451	71627.33
272	1	6	2	18	1	3	0.0007	51.9877	73393.58
273	1	6	2	18	1	4	0.0007	53.2818	75159.83
274	1	6	2	18	2	2	0.0007	51.3858	72688.00
275	1	6	2	18	2	3	0.0007	52.5932	74142.50
276	1	6	2	18	2	4	0.0007	53.8464	76066.50
277	1	6	2	19	1	2	0.0007	51.9982	73393.58
278	1	6	2	19	1	3	0.0007	53.2291	75159.83
279	1	6	2	19	1	4	0.0007	54.4472	76762.75
280	1	6	2	19	2	2	0.0007	52.6376	74300.25
281	1	6	2	19	2	3	0.0007	53.941	76066.50
282	1	6	2	19	2	4	0.0007	55.1175	77998.00
283	1	6	2	20	1	2	0.0007	53.2611	75319.40
284	1	6	2	20	1	3	0.0007	54.5227	77089.40
285	1	6	2	20	1	4	0.0007	55.7587	78692.33
286	1	6	2	20	2	2	0.0007	53.9338	76228.00
287	1	6	2	20	2	3	0.0007	55.1742	77998.00
288	1	6	2	20	2	4	0.0007	56.421	79768.00
289	2	3	1	15	1	2	0.0008	43.561	53343.83
290	2	3	1	15	1	3	0.0008	44.7307	54743.40
291	2	3	1	15	1	4	0.0008	46.07	56411.33
292	2	3	1	15	2	2	0.0008	44.1797	54131.15
293	2	3	1	15	2	3	0.0008	45.3827	55664.90
294	2	3	1	15	2	4	0.0008	46.6905	57198.65
295	2	3	1	16	1	2	0.0008	44.8256	55011.75
296	2	3	1	16	1	3	0.0008	46.0591	56411.33
297	2	3	1	16	1	4	0.0008	47.2605	57945.08
298	2	3	1	16	2	2	0.0008	45.4415	55801.00
299	2	3	1	16	2	3	0.0008	46.6707	57058.80
300	2	3	1	16	2	4	0.0008	47.9141	58732.40
301	2	3	1	17	1	2	0.0008	46.075	56549.25
302	2	3	1	17	1	3	0.0008	47.2953	57945.08
303	2	3	1	17	1	4	0.0008	48.5502	59624.25
304	2	3	1	17	2	2	0.0008	46.6975	57198.65

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
305	2	3	1	17	2	3	0.0008	47.9079	58732.40
306	2	3	1	17	2	4	0.0008	49.1558	60413.50
307	2	3	1	18	1	2	0.0008	47.3184	57945.08
308	2	3	1	18	1	3	0.0008	48.5585	59478.83
309	2	3	1	18	1	4	0.0008	49.7724	60863.40
310	2	3	1	18	2	2	0.0008	47.9766	58732.40
311	2	3	1	18	2	3	0.0008	49.1683	60413.50
312	2	3	1	18	2	4	0.0008	50.4334	61951.00
313	2	3	1	19	1	2	0.0008	48.5206	59333.40
314	2	3	1	19	1	3	0.0008	49.7279	60863.40
315	2	3	1	19	1	4	0.0008	51.094	62699.25
316	2	3	1	19	2	2	0.0008	49.2275	60266.15
317	2	3	1	19	2	3	0.0008	50.4204	61648.80
318	2	3	1	19	2	4	0.0008	51.7356	63333.65
319	2	3	1	20	1	2	0.0008	49.8449	61161.75
320	2	3	1	20	1	3	0.0008	51.0549	62546.33
321	2	3	1	20	1	4	0.0008	52.2984	64080.08
322	2	3	1	20	2	2	0.0008	50.3688	61648.80
323	2	3	1	20	2	3	0.0008	51.7257	63178.80
324	2	3	1	20	2	4	0.0008	52.9757	64867.40
325	2	3	2	15	1	2	0.0008	46.3294	56403.55
326	2	3	2	15	1	3	0.0008	47.6381	58068.73
327	2	3	2	15	1	4	0.0008	48.86	59594.98
328	2	3	2	15	2	2	0.0008	47.0455	57466.80
329	2	3	2	15	2	3	0.0008	48.2868	58852.20
330	2	3	2	15	2	4	0.0008	49.5177	60378.45
331	2	3	2	16	1	2	0.0008	47.6082	58068.73
332	2	3	2	16	1	3	0.0008	48.8319	59594.98
333	2	3	2	16	1	4	0.0008	50.0987	61121.23
334	2	3	2	16	2	2	0.0008	48.2497	58852.20
335	2	3	2	16	2	3	0.0008	49.4945	60526.80
336	2	3	2	16	2	4	0.0008	50.7053	61904.70
337	2	3	2	17	1	2	0.0008	48.8137	59594.98
338	2	3	2	17	1	3	0.0008	50.0967	60971.05
339	2	3	2	17	1	4	0.0008	51.4058	62801.40
340	2	3	2	17	2	2	0.0008	49.4526	60230.10
341	2	3	2	17	2	3	0.0008	50.743	61752.60
342	2	3	2	17	2	4	0.0008	52.0293	63430.95
343	2	3	2	18	1	2	0.0008	50.1727	61121.23
344	2	3	2	18	1	3	0.0008	51.3485	62493.55
345	2	3	2	18	1	4	0.0008	52.5967	64016.05
346	2	3	2	18	2	2	0.0008	50.7502	61904.70
347	2	3	2	18	2	3	0.0008	52.0258	63275.10
348	2	3	2	18	2	4	0.0008	53.211	64797.60

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
349	2	3	2	19	1	2	0.0008	51.3856	62493.55
350	2	3	2	19	1	3	0.0008	52.6578	64173.73
351	2	3	2	19	1	4	0.0008	53.8118	65538.55
352	2	3	2	19	2	2	0.0008	52.0754	63430.95
353	2	3	2	19	2	3	0.0008	53.2003	64797.60
354	2	3	2	19	2	4	0.0008	54.4924	66320.10
355	2	3	2	20	1	2	0.0008	52.6587	64173.73
356	2	3	2	20	1	3	0.0008	53.8214	65699.98
357	2	3	2	20	1	4	0.0008	55.1675	67226.23
358	2	3	2	20	2	2	0.0008	53.2507	64957.20
359	2	3	2	20	2	3	0.0008	54.5039	66483.45
360	2	3	2	20	2	4	0.0008	55.808	68009.70
361	2	4	1	15	1	2	0.0008	44.795	53133.30
362	2	4	1	15	1	3	0.0008	45.9831	54342.45
363	2	4	1	15	1	4	0.0008	47.2851	55819.95
364	2	4	1	15	2	2	0.0008	45.3852	53759.50
365	2	4	1	15	2	3	0.0008	46.6711	55240.75
366	2	4	1	15	2	4	0.0008	47.9359	56865.60
367	2	4	1	16	1	2	0.0008	46.0451	54480.38
368	2	4	1	16	1	3	0.0008	47.2416	55961.63
369	2	4	1	16	1	4	0.0008	48.567	57588.30
370	2	4	1	16	2	2	0.0008	46.6625	55380.60
371	2	4	1	16	2	3	0.0008	47.9786	57009.20
372	2	4	1	16	2	4	0.0008	49.1951	58203.25
373	2	4	1	17	1	2	0.0008	47.2687	55961.63
374	2	4	1	17	1	3	0.0008	48.572	57588.30
375	2	4	1	17	1	4	0.0008	49.7334	59073.30
376	2	4	1	17	2	2	0.0008	47.9728	56722.00
377	2	4	1	17	2	3	0.0008	49.14	58203.25
378	2	4	1	17	2	4	0.0008	50.4934	59835.60
379	2	4	1	18	1	2	0.0008	48.5556	57442.88
380	2	4	1	18	1	3	0.0008	49.7873	59073.30
381	2	4	1	18	1	4	0.0008	51.0077	60558.30
382	2	4	1	18	2	2	0.0008	49.2293	58350.60
383	2	4	1	18	2	3	0.0008	50.3685	59684.50
384	2	4	1	18	2	4	0.0008	51.7198	61320.60
385	2	4	1	19	1	2	0.0008	49.8435	59073.30
386	2	4	1	19	1	3	0.0008	50.9993	60405.38
387	2	4	1	19	1	4	0.0008	52.243	62043.30
388	2	4	1	19	2	2	0.0008	50.4099	59835.60
389	2	4	1	19	2	3	0.0008	51.67	61320.60
390	2	4	1	19	2	4	0.0008	52.9958	62805.60
391	2	4	1	20	1	2	0.0008	51.031	60405.38
392	2	4	1	20	1	3	0.0008	52.306	62043.30

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
393	2	4	1	20	1	4	0.0008	53.4949	63367.88
394	2	4	1	20	2	2	0.0008	51.6254	61165.75
395	2	4	1	20	2	3	0.0008	52.8773	62647.00
396	2	4	1	20	2	4	0.0008	54.1408	63965.90
397	2	4	2	15	1	2	0.0008	47.6418	56213.95
398	2	4	2	15	1	3	0.0008	48.8715	57691.45
399	2	4	2	15	1	4	0.0008	50.0676	59168.95
400	2	4	2	15	2	2	0.0008	48.2897	56972.40
401	2	4	2	15	2	3	0.0008	49.4822	58301.55
402	2	4	2	15	2	4	0.0008	50.746	59927.40
403	2	4	2	16	1	2	0.0008	48.8483	57545.03
404	2	4	2	16	1	3	0.0008	50.1495	59168.95
405	2	4	2	16	1	4	0.0008	51.3727	60492.53
406	2	4	2	16	2	2	0.0008	49.5238	58301.55
407	2	4	2	16	2	3	0.0008	50.737	59775.30
408	2	4	2	16	2	4	0.0008	52.0254	61249.05
409	2	4	2	17	1	2	0.0008	50.145	59168.95
410	2	4	2	17	1	3	0.0008	51.4261	60800.38
411	2	4	2	17	1	4	0.0008	52.6175	62123.95
412	2	4	2	17	2	2	0.0008	50.7879	59927.40
413	2	4	2	17	2	3	0.0008	52.0542	61404.90
414	2	4	2	17	2	4	0.0008	53.303	62722.80
415	2	4	2	18	1	2	0.0008	51.3754	60646.45
416	2	4	2	18	1	3	0.0008	52.6608	62123.95
417	2	4	2	18	1	4	0.0008	53.8088	63440.03
418	2	4	2	18	2	2	0.0008	51.9583	61404.90
419	2	4	2	18	2	3	0.0008	53.2861	62882.40
420	2	4	2	18	2	4	0.0008	54.4727	64196.55
421	2	4	2	19	1	2	0.0008	52.6453	61966.28
422	2	4	2	19	1	3	0.0008	53.883	63440.03
423	2	4	2	19	1	4	0.0008	55.1429	65078.95
424	2	4	2	19	2	2	0.0008	53.2077	62722.80
425	2	4	2	19	2	3	0.0008	54.5212	64359.90
426	2	4	2	19	2	4	0.0008	55.7235	65670.30
427	2	4	2	20	1	2	0.0008	53.8104	63440.03
428	2	4	2	20	1	3	0.0008	55.1746	65078.95
429	2	4	2	20	1	4	0.0008	56.3887	66387.53
430	2	4	2	20	2	2	0.0008	54.5596	64359.90
431	2	4	2	20	2	3	0.0008	55.8202	65837.40
432	2	4	2	20	2	4	0.0008	57.0687	67144.05
433	2	5	1	15	1	2	0.0009	46.0638	53239.05
434	2	5	1	15	1	3	0.0009	47.3389	54828.23
435	2	5	1	15	1	4	0.0009	48.5447	56134.05
436	2	5	1	15	2	2	0.0009	46.6953	53982.10

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
437	2	5	1	15	2	3	0.0009	47.9195	55429.60
438	2	5	1	15	2	4	0.0009	49.1209	56877.10
439	2	5	1	16	1	2	0.0009	47.3295	54828.23
440	2	5	1	16	1	3	0.0009	48.5029	56134.05
441	2	5	1	16	1	4	0.0009	49.7382	57581.55
442	2	5	1	16	2	2	0.0009	47.9771	55429.60
443	2	5	1	16	2	3	0.0009	49.1417	56729.75
444	2	5	1	16	2	4	0.0009	50.4917	58626.80
445	2	5	1	17	1	2	0.0009	48.5781	56279.48
446	2	5	1	17	1	3	0.0009	49.7474	57581.55
447	2	5	1	17	1	4	0.0009	51.0972	58876.13
448	2	5	1	17	2	2	0.0009	49.179	57024.45
449	2	5	1	17	2	3	0.0009	50.4293	58324.60
450	2	5	1	17	2	4	0.0009	51.6448	59772.10
451	2	5	1	18	1	2	0.0009	49.7861	57730.73
452	2	5	1	18	1	3	0.0009	51.0169	59029.05
453	2	5	1	18	1	4	0.0009	52.2521	60476.55
454	2	5	1	18	2	2	0.0009	50.4403	58475.70
455	2	5	1	18	2	3	0.0009	51.6549	59772.10
456	2	5	1	18	2	4	0.0009	52.8999	61061.00
457	2	5	1	19	1	2	0.0009	51.0227	59029.05
458	2	5	1	19	1	3	0.0009	52.3125	60476.55
459	2	5	1	19	1	4	0.0009	53.5873	62084.48
460	2	5	1	19	2	2	0.0009	51.747	59926.95
461	2	5	1	19	2	3	0.0009	52.9197	61219.60
462	2	5	1	19	2	4	0.0009	54.1959	62667.10
463	2	5	1	20	1	2	0.0009	52.3083	60476.55
464	2	5	1	20	1	3	0.0009	53.5696	62084.48
465	2	5	1	20	1	4	0.0009	54.756	63207.38
466	2	5	1	20	2	2	0.0009	52.8732	61061.00
467	2	5	1	20	2	3	0.0009	54.2245	62667.10
468	2	5	1	20	2	4	0.0009	55.4767	64114.60
469	2	5	2	15	1	2	0.0009	48.9053	56080.78
470	2	5	2	15	1	3	0.0009	50.068	57366.85
471	2	5	2	15	1	4	0.0009	51.3278	58799.35
472	2	5	2	15	2	2	0.0009	49.4952	56521.35
473	2	5	2	15	2	3	0.0009	50.7948	58254.30
474	2	5	2	15	2	4	0.0009	51.9524	59534.70
475	2	5	2	16	1	2	0.0009	50.1486	57366.85
476	2	5	2	16	1	3	0.0009	51.4261	58953.28
477	2	5	2	16	1	4	0.0009	52.5885	60074.18
478	2	5	2	16	2	2	0.0009	50.7976	58102.20
479	2	5	2	16	2	3	0.0009	52.0606	59534.70
480	2	5	2	16	2	4	0.0009	53.2959	60967.20

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
481	2	5	2	17	1	2	0.0009	51.3337	58799.35
482	2	5	2	17	1	3	0.0009	52.6069	60231.85
483	2	5	2	17	1	4	0.0009	53.8849	61664.35
484	2	5	2	17	2	2	0.0009	52.0027	59690.55
485	2	5	2	17	2	3	0.0009	53.2008	60967.20
486	2	5	2	17	2	4	0.0009	54.5446	62399.70
487	2	5	2	18	1	2	0.0009	52.6841	60389.53
488	2	5	2	18	1	3	0.0009	53.891	61664.35
489	2	5	2	18	1	4	0.0009	55.2011	63096.85
490	2	5	2	18	2	2	0.0009	53.2958	60807.60
491	2	5	2	18	2	3	0.0009	54.4774	62399.70
492	2	5	2	18	2	4	0.0009	55.8306	63832.20
493	2	5	2	19	1	2	0.0009	53.9297	61664.35
494	2	5	2	19	1	3	0.0009	55.0693	62931.68
495	2	5	2	19	1	4	0.0009	56.338	64529.35
496	2	5	2	19	2	2	0.0009	54.485	62399.70
497	2	5	2	19	2	3	0.0009	55.7842	63999.30
498	2	5	2	19	2	4	0.0009	57.0506	65264.70
499	2	5	2	20	1	2	0.0009	55.1968	63262.03
500	2	5	2	20	1	3	0.0009	56.3918	64529.35
501	2	5	2	20	1	4	0.0009	57.5879	65789.18
502	2	5	2	20	2	2	0.0009	55.7463	63832.20
503	2	5	2	20	2	3	0.0009	57.0359	65264.70
504	2	5	2	20	2	4	0.0009	58.2957	66522.60
505	2	6	1	15	1	2	0.0009	47.3431	54403.20
506	2	6	1	15	1	3	0.0009	48.5797	55697.78
507	2	6	1	15	1	4	0.0009	49.7471	56835.68
508	2	6	1	15	2	2	0.0009	47.9458	54855.20
509	2	6	1	15	2	3	0.0009	49.2154	56287.70
510	2	6	1	15	2	4	0.0009	50.4548	57720.20
511	2	6	1	16	1	2	0.0009	48.5647	55552.35
512	2	6	1	16	1	3	0.0009	49.8363	57134.03
513	2	6	1	16	1	4	0.0009	51.0656	58570.28
514	2	6	1	16	2	2	0.0009	49.1196	56140.35
515	2	6	1	16	2	3	0.0009	50.4045	57720.20
516	2	6	1	16	2	4	0.0009	51.6764	59307.55
517	2	6	1	17	1	2	0.0009	49.7819	56984.85
518	2	6	1	17	1	3	0.0009	50.9937	58570.28
519	2	6	1	17	1	4	0.0009	52.2548	59849.85
520	2	6	1	17	2	2	0.0009	50.4626	57720.20
521	2	6	1	17	2	3	0.0009	51.6311	58997.85
522	2	6	1	17	2	4	0.0009	52.952	60585.20
523	2	6	1	18	1	2	0.0009	51.0642	58570.28
524	2	6	1	18	1	3	0.0009	52.2378	59849.85

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
525	2	6	1	18	1	4	0.0009	53.4799	61442.78
526	2	6	1	18	2	2	0.0009	51.726	59307.55
527	2	6	1	18	2	3	0.0009	52.8928	60585.20
528	2	6	1	18	2	4	0.0009	54.1478	62017.70
529	2	6	1	19	1	2	0.0009	52.2438	59693.18
530	2	6	1	19	1	3	0.0009	53.5756	61282.35
531	2	6	1	19	1	4	0.0009	54.7813	62714.85
532	2	6	1	19	2	2	0.0009	52.9117	60426.60
533	2	6	1	19	2	3	0.0009	54.2267	62180.05
534	2	6	1	19	2	4	0.0009	55.4166	63450.20
535	2	6	1	20	1	2	0.0009	53.5682	61442.78
536	2	6	1	20	1	3	0.0009	54.7746	62714.85
537	2	6	1	20	1	4	0.0009	56.1171	64315.28
538	2	6	1	20	2	2	0.0009	54.2135	62017.70
539	2	6	1	20	2	3	0.0009	55.4902	63450.20
540	2	6	1	20	2	4	0.0009	56.6805	65052.55
541	2	6	2	15	1	2	0.0009	50.1693	57216.68
542	2	6	2	15	1	3	0.0009	51.4195	58645.43
543	2	6	2	15	1	4	0.0009	52.6649	60074.18
544	2	6	2	15	2	2	0.0009	50.7375	57950.10
545	2	6	2	15	2	3	0.0009	52.0098	59223.00
546	2	6	2	15	2	4	0.0009	53.2515	60488.40
547	2	6	2	16	1	2	0.0009	51.3158	58491.50
548	2	6	2	16	1	3	0.0009	52.6067	60074.18
549	2	6	2	16	1	4	0.0009	53.908	61502.93
550	2	6	2	16	2	2	0.0009	52.0738	59223.00
551	2	6	2	16	2	3	0.0009	53.3081	60807.60
552	2	6	2	16	2	4	0.0009	54.5924	62236.35
553	2	6	2	17	1	2	0.0009	52.6284	60074.18
554	2	6	2	17	1	3	0.0009	53.8146	61341.50
555	2	6	2	17	1	4	0.0009	55.0953	62766.50
556	2	6	2	17	2	2	0.0009	53.3067	60648.00
557	2	6	2	17	2	3	0.0009	54.4564	62236.35
558	2	6	2	17	2	4	0.0009	55.7677	63498.00
559	2	6	2	18	1	2	0.0009	53.8231	61341.50
560	2	6	2	18	1	3	0.0009	55.1808	62766.50
561	2	6	2	18	1	4	0.0009	56.4188	64191.50
562	2	6	2	18	2	2	0.0009	54.5441	62073.00
563	2	6	2	18	2	3	0.0009	55.7832	63498.00
564	2	6	2	18	2	4	0.0009	57.0566	64923.00
565	2	6	2	19	1	2	0.0009	55.1836	62931.68
566	2	6	2	19	1	3	0.0009	56.3413	64360.43
567	2	6	2	19	1	4	0.0009	57.5855	65443.83
568	2	6	2	19	2	2	0.0009	55.8124	63498.00

Scenarios Number	CRANE	LABOR	PUMP TRUCK	LABOR	BIDWELL	LABOR	Prod. Per Unit Time	Cost Per Unit Time	Cost Per Prod. Unit
569	2	6	2	19	2	3	0.0009	57.0589	64923.00
570	2	6	2	19	2	4	0.0009	58.2359	66348.00
571	2	6	2	20	1	2	0.0009	56.4141	64191.50
572	2	6	2	20	1	3	0.0009	57.6219	65443.83
573	2	6	2	20	1	4	0.0009	58.8683	66865.08
574	2	6	2	20	2	2	0.0009	57.0533	64923.00
575	2	6	2	20	2	3	0.0009	58.205	66348.00
576	2	6	2	20	2	4	0.0009	59.5487	67773.00

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