# Application of FRP Composites to Bridges in the USA

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The history and the current state-of-the-art related to the use of Fiber Reinforced Polymer (FRP) composite materials in bridges in the USA is reviewed in this paper. The paper addresses three key application areas: (1) Pedestrian bridges made of only FRP components, (2) Highway bridge decks and girders made of only FRP components, (3) Highway bridge systems made of hybrid reinforced concrete and FRP components. The primary emphasis of the paper is on the use of pultruded FRP materials in bridge applications. The paper discusses only those FRP bridges and bridge components that have actually been applied in the field in the USA and does not discuss laboratory and conceptual studies. For each application area the paper briefly addresses the subjects of FRP material selection, analysis methods, design methods, construction methods, and costs.

*Key Words: Pedestrian bridges, highway bridges, bridge decks, pultruded composites*

## 1. Introduction

The use of FRP materials in pedestrian and vehicular bridges in the USA has been the subject of increasing research and development since the late 1980s, however early interest in the use of FRP materials in bridges dates back to the early 1970s[1]. Encouraged by the growing acceptance of advanced composite materials in the sporting goods industries (and aerospace to a lesser extent) and the potential for a corrosion resistant construction material the Federal Highway Administration (FHWA) and the National Science Foundation (NSF) in the late 1980s, began increasing funding to enable research on FRP materials for infrastructure applications. Much of the work was focused on bridges as highway bridge deterioration in the USA in the mid-1980s was regarded as a pressing national concern. Early interest was on FRP only bridge decks (and pedestrian bridges) and FRP reinforcement for concrete decks. In the early 1990s interest in seismic rehabilitation using FRP materials began. This increased dramatically after the 1994 Northridge earthquake, and the use of FRP sheets and fabrics overtook the FRP only development. By the later 1990s and early 2000s, however, interest returned to FRP materials for vehicular bridges, encouraged to a large part by the Innovative Bridge Research and Construction (IBRC) Program of the FHWA which enabled many FRP bridge components to move into the application phase. At the time of writing, in late 2005, there are over 300 FRP pedestrian bridges and approximately 50 highway bridges with FRP decks or girders in the USA. In addition, there are a handful of hybrid FRP and concrete bridges that have been built. The vast majority of these bridges and components have used pultruded FRP components, and therefore the paper focuses mainly on applications involving pultruded composites.

## 2. FRP Pedestrian Bridges

Three types of FRP structural systems are currently used to construct FRP pedestrian bridges in the USA. These are (1) Truss bridges using small-sized (75 to 150 mm) pultruded profiles, (2) Cable supported bridges using small-sized pultruded profiles and non-metallic cables, and (3) Girder bridges using large-sized (300 to 600 mm) pultruded profiles. Many of these pedestrian bridges are also designed to carry small vehicles (up to 10 tons (89 kN)) that are used for snow removal or in emergencies. Pedestrian bridges in the USA are typically designed in accordance with the AASHTO Guide Specification for Design of Pedestrian Bridges[2] for a live load of 415 kg/m$^2$, a deflection less than L/180 and a fundamental frequency greater than 3 Hz.

<u>(1) Truss bridges</u>

Truss type bridges made from small-sized pultruded FRP profiles have become an economical alternative for pedestrian bridges in the USA where light-weight, durability, appearance, and ease of construction are important considerations. A typical pultruded truss bridge in Point Bonita, CA designed by ETTechtonics in Pennsylvania, USA is shown in Fig. 1.

Fig. 1 24 m long FRP pedestrian truss bridge

FRP truss bridges are most effective for spans of between 9 and 30 m and have widths from 1.5 to 3.0 m. Typical pultruded structural shapes used in these bridges are back-to-back channel sections with a height of 150 mm for the top and bottom chords, 50 mm square tube sections for the posts and diagonals, and 75 mm channels sections for non-structural side barriers. Horizontal bracing members (typically channels) under the deck and outriggers seen in Fig. 1 are usually used for lateral stability for longer spans. These can be seen in the end-view of the bridge shown in Fig. 2.

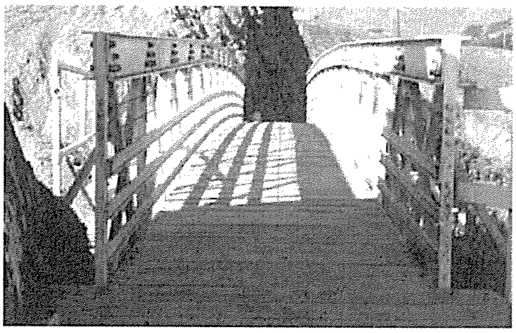

Fig. 2 End view of pultruded truss bridge

Truss bridges are typically connected using galvanized or stainless steel bolts and nuts. Treated lumber is usually used for the deckling. Pultruded grating and other FRP decking materials have also been used but timber decking is usually more economical (although still a major source of the bridge cost). Glass-polyester pultruded materials are most often specified for these bridges. The 17.2 GPa longitudinal modulus of the pultruded material is typically the controlling factor in the design. Truss bridges are often designed with a camber to decrease deflections under dead loads.

Truss bridges are analyzed using conventional structural analysis methods using linear elastic (orthotropic) materials and small deflection assumptions. Detailing plays a major part in the design. Connections are designed as bearing connections and one or two bolts are used to transfer in-plane loads between connected members. Gusset plates and additional parts are avoided by using overlapping members or inserts. Results of tests on pultruded members for single and double bolt connections with inserts are used in design[3]. The bridges are typically assembled on-site and lifted into place or depolyed. Concrete foundations and abutments are usually used to support the bridge. The cost of pultruded truss bridges depends on the span length and can be significantly influenced by the cost of the installation and foundation system. In general, the following can be used as a guideline: Bridges under 15 m (\$540-650/m$^2$), 15-24m (\$750-860/m$^2$) and 24-30m (\$915-1,075/m$^2$).

(2) Cable-supported bridges

Cable supported FRP bridges made of pultruded members are supported using post-tensioned cables that run under the deck to vertical posts (either single "king posts" or double "queen posts") extending downwards. This familiar historical structural system is particularly effective for FRP bridges due to the low stiffness of glass-FRP materials. An early Prestek® cable supported pultruded farm-bridge is shown in Fig. 3.

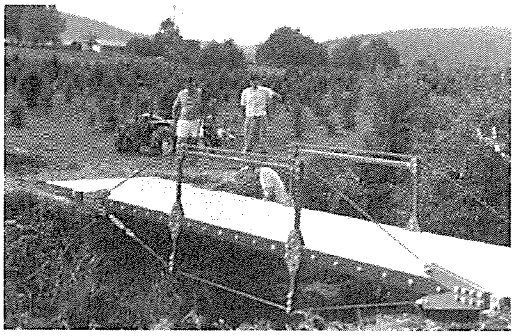

Fig. 3 Prestek® Cable supported FRP pedestrian farm bridge (photo: ETTechtonics)

Cable supported FRP pedestrian bridges are often aesthetically very pleasing. They are typically used on shorter spans than FRP truss bridges, in the range of 6 to 20 m. Since they do not require diagonal braces like truss-bridges they have a much lighter and more elegant appearance. However, a guardrail must typically be installed if the bridge is to be used as a pedestrian bridge, which requires a separate rail system (the top cable in the bridge in Fig. 3 can serve this purpose). Non-metallic sheathed aramid cables with potted cast-iron clevis ends are used in these systems. The cables are anchored to the main longitudinal beams and are tensioned using a turnbuckle. The anchorage region requires a fairly elaborate FRP gusset plate detail (see Fig. 3.) The cable can be used to pre-camber the bridge or to stiffen the bridge if long-term deformation occurs, however, a cable bridge must not be used if there is insufficient clearance and the cable can be subjected to lateral loading. In addition, the posts need to be suitably supported and connected to the main longitudinal beams. Cable supported bridges can be constructed to any width since multiple cables and longitudinal beams can be run under the bridge. The system has been used to construct a variety of bridges and can even be used as a three-dimensional building system[4] as shown in Fig. 4. A combination truss and cable FRP bridge that uses the system has been tested for highway vehicle loads[5].

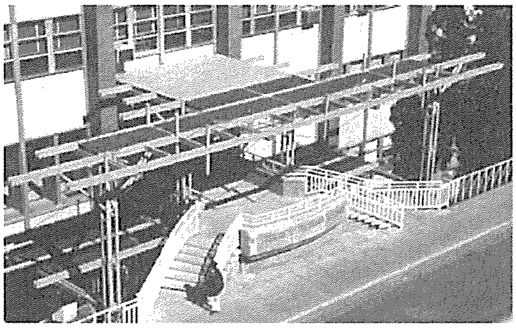

Fig. 4 Cable-supported FRP building system

(3) Girder bridges

Pedestrian girder bridges are constructed in a similar fashion to vehicular girder bridges and use deep pultruded I sections as the primary flexural members. A number of pultrusion companies in the US produce I sections or channel sections having depths of 450 and 600 mm, flange widths of 100 to 200 mm, and wall thicknesses of 4 to 19 mm. These deep I beams (or back-to-back channels) are used at spacings of 900 to 1200 mm and are cross-braced with small pultruded angles and tubes for lateral stability. A 13.5 m bridge using 600 mm deep glass-vinylester I-beams in a wastewater treatment plant is shown in Fig. 5.

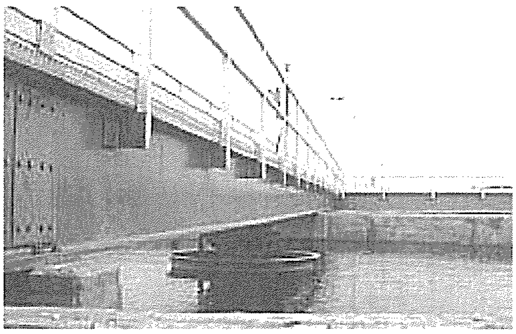

Fig. 5 FRP I-girder bridge (photo: Strongwell)

Due to the low longitudinal modulus of glass-vinylester pultrusions (19 GPa) girder bridges of this type are limited to approximately 15 m spans due to deflection constraints. In order to increase the stiffness of an FRP girder bridge carbon fibers have been included in the flanges of 600 mm deep I-sections. A 18.3 m long pedestrian bridge, constructed using two glass-carbon "hybrid" pultruded I girders in 1996, in Kentucky[6] is shown in Fig. 6. The inclusion of the carbon fiber in the flanges raised the effective full-section flexural modulus of the profile to 39.3 GPa, however, this was still not sufficient to meet deflection limits (L/180). A cable queen-post system anchored at the abutments was also used. This bridge used an open-grating pultruded decking material.

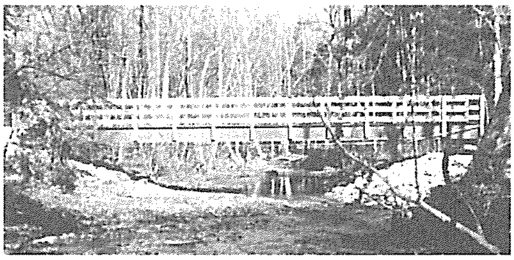

Fig. 6 Hybrid FRP girder bridge with cable (photo: Strongwell)

## 3. FRP Highway Bridges

FRP components for vehicular bridges (including highway bridges) include bridge girders and bridge deck panels. Efforts to develop FRP bridge deck panels to replace reinforced concrete bridge decks (primarily) were initiated by the FHWA in the mid 1980s. The development of FRP girders for highway bridges began in the mid 1990s. FRP girder and deck components have been typically designed for HS20-44 highway loads according to the AASHTO Standard Specification for Highway Bridges[7]. The standard truck weight for this loading is a 36 ton (320 kN) tractor-trailer (3 axels). Both girders and decks are usually designed for a L/800 deflection limit.

(1) Highway bridge girders

FRP highway bridge girders were first developed and applied in the mid-1990s as part of all FRP bridge system that were integrated with FRP decks. Later FRP girders only were develop for use with a variety of deck systems including concrete and timber. The first two FRP girder bridges constructed in the USA were short span bridges that used molded box-type girders. Fig. 7 shows molded U shaped girders for installation in a 9.1 m long bridge (the INEEL bridge) in 1995. Fig. 8 shows molded trapezoidal box girders for installation in a 10.1 m long bridge (the Tech 21 bridge) in 1997[8,9]. Both bridges were designed by the Lockheed Martin Advanced Technology Group in Palo Alto, CA and had first generation FRP decks made of bonded pultruded square or trapezoidal tubes with face sheets. All FRP materials were glass fiber reinforced with polyester or vinylester resins.

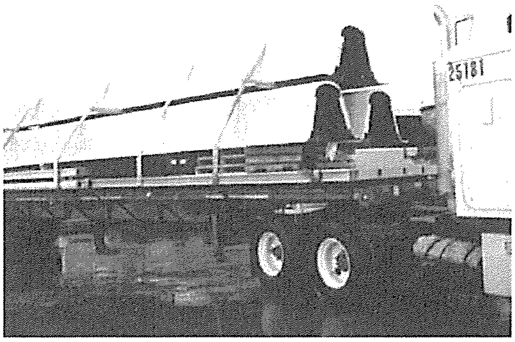


Fig. 7 Molded U-girders (upside down) for INEEL bridge (photo: Martin Marietta Composites)

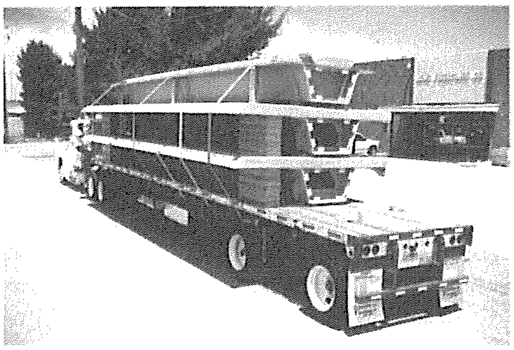

Fig. 8 Molded trapezoidal girders (with FRP deck) for the TECH 21 bridge (photo: Martin Marietta Composites)

A pultruded hybrid FRP girder called the Double Web Beam (DWB) with depth of either 200 mm or 900 mm was developed by Strongwell in Bristol, VA in the late 1990s. The girder is a stand-alone FRP bridge girder that can be used in spans of up to 15 m. Similar to the earlier hybrid I-beam developed by Strongwell and used in the Kentucky footbridge (Fig. 6) the girder flange is a hybrid of glass and carbon fiber and the webs are glass fiber in a vinylester resin. The full-section flexural modulus of the beam is 42 GPa. The smaller girder was first used in 1997 in a 5.5. m long bridge (the Tom's Creek Bridge)[10]. The larger DWB beam was used in a 11.9 m long bridge in 2001 (the Route 601 bridge)[11]. Seven DWG girders were spaced transversely at 1.1 m across the bridge that had a total width of 9.7 m. Installation of the FRP girders is shown in Fig. 9. The timber guardrail attached to the deck is shown in Fig. 10. Both bridges have glue-laminated panel timber decking and asphalt wearing surfaces. The 900 mm deep hybrid DWB beam weighs 112 kg/m and currently sells for around $1,600/m.

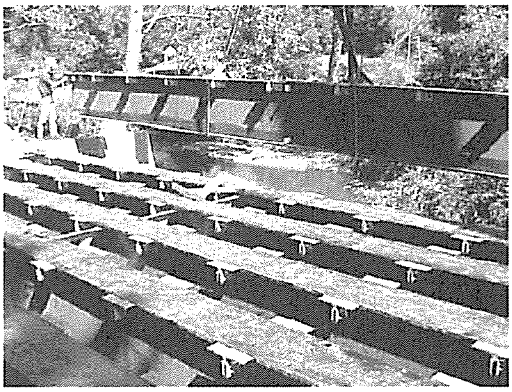

Fig. 9 Installation of FRP Double web pultruded girders on Rt. 601 bridge (photo: Strongwell)

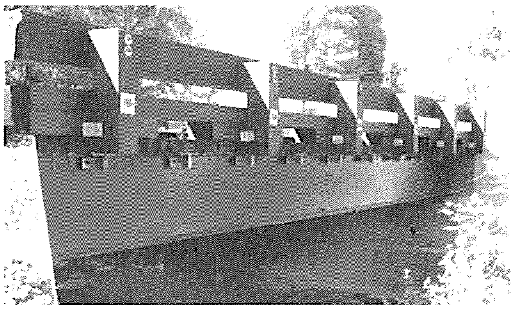

Fig. 10 Timber guardrail and deck on Rt. 601 bridge (photo: Strongwell)

Recently Molded Fiber Glass (MFG) developed a molded U-shaped girder for use with a reinforced concrete deck (called a hybrid FRP bridge system). The girder is molded and has steel shear transfer rods to allow it to act compositely with the concrete deck that is cast in the field on the girders. The trough of the U is filled with foam to prevent the concrete from filling the girder. Twenty-four girders were installed in Texas on a 8.8 m long bridge in 2004 (The San Patricio County bridge)[12]. The girders during shipping are shown in Fig. 11. Fig. 12 shows the installed FRP U-beams prior to casting of the concrete deck.. The U beam weighs 122 kg/m and currently sells for $1,350/m.

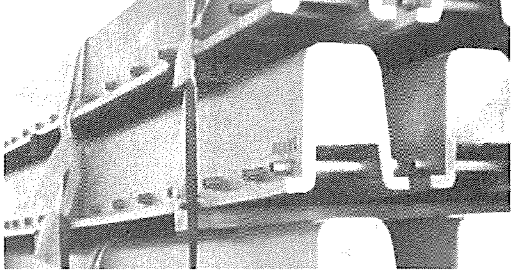

Fig. 11 Molded FRP U-girders for Texas bridge (inverted for shipping) (photo: MFG)

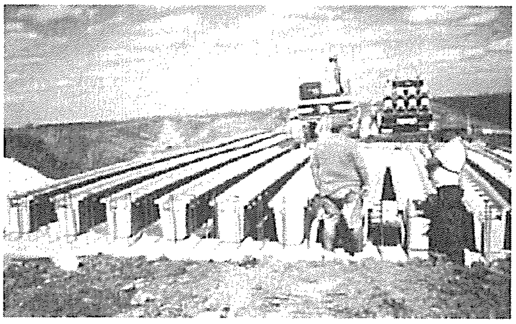

Fig. 12 Molded FRP U-girders installed on abutments (photo: MFG)

(2) Highway bridge decks

Bridge deck systems for non-girder short slab-type bridges and traditional girder bridges have been developed in the USA. Both molded sandwich decks and pultruded decks have been produced[13]. Research into the use of tubular FRP elements to form a multi-cell, truss-type, bridge deck panel began in the mid 1980s and was supported by the FHWA[14]. During this early period individual triangular shaped filament wound tubes were bonded together with FRP face sheets to form a panel shown in Fig. 13. This deck was never manufactured in larger elements nor was it ever installed in a bridge, however, it paved the way for the development of the pultruded decks of the late 1990s. Numerical studies were also conducted on the optimal configurations of the truss-elements in these decks[14].

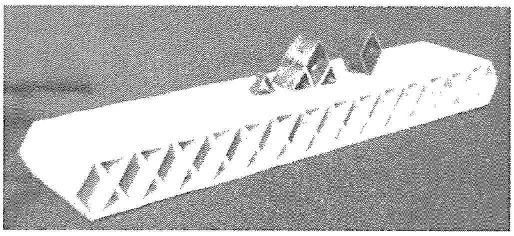

Fig. 13 FRP deck developed by Plecnick and co-workers

In the early 1990s, a number of studies were conducted to develop cellular decks using pultruded tubular elements that were bonded together with FRP face sheets to form modular deck panels. The earliest of these "laid-up" deck panels were installed on the INEEL (shown in Fig. 14) and TECH 21 bridges in 1995 and 1997. The deck panels for the Tech 21 bridge were pre-attached to the girders as shown in Fig. 8.

In this same period, Kansas Structural Composites developed a molded sandwich panel with a honeycomb FRP core which was installed in a 7 m long slab-bridge (no girders) in Russell County, Kansas in 1996. This system was also used in a 8 m long bridge in Missouri in 2000 (the St. James bridge)[15], and 14.6 m wide panels of this system were installed in a multi span bridge in Ohio in 1999 (Salem Avenue Bridge)[16].

Fig. 14. First FRP deck panel installed in the USA in 1995 (photo: Martin Marietta Composites)

A molded Vacuum Assisted Resin Transfer Molded (VARTM) foam-core sandwich deck was developed by Hardcore Composites (no longer in business) and installed on a number of bridges in the USA in the late 1990s and early 2000. Installation of 12 m long by 2.4 m wide molded panels on steel truss bridge in New York in 1999 is shown in Fig. 15. Hardcore panels were also used on the Salem Avenue Bridge in Ohio[16].

Fig. 15 Installation of molded panels on steel stringer bridge (photo: J. O'Connor)

Pultruded decks continued to be developed in the late 1990s[17] and the FHWA funded research from 1998 to 2002 to conduct studies to develop material and structural specifications for FRP materials for use in bridges[18,19]. In the late 1990s multi-cellular pultruded panels were developed using (a) triangular (EZ-Span, Atlantic Research Corporation)[20], (b) hexagonal (Superdeck – Creative Pultrusions)[21], (c) trapezoidal (Duraspan, Martin Marietta Composites), and (d) square tube assemblies (Strongwell)[22] that have all been installed in either bridges or experimental road test sites in the USA. The four different deck types[13] are shown graphically in Fig. 16.

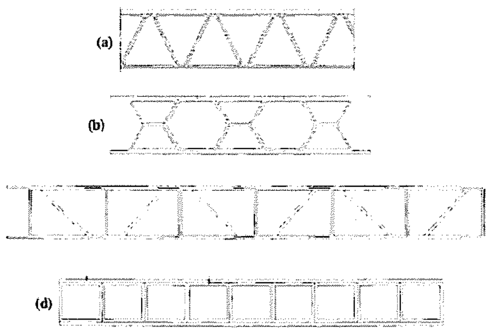


Fig. 16 FRP pultruded decks produced in the USA in the late 1990s (from Bakis et al, 2001)

The Superdeck was the first modular FRP pultruded deck installed in the USA. It was installed on a 6.1 m long bridge (Laurel Lick Bridge) and on a 9.2 m long bridge (Wickwire Run Bridge) in 1997[21]. Installation of the FRP deck panels on the Wickwire run bridge is shown in Fig. 17. Superdeck panels were also used on the Salem Ave bridge in Ohio[16].

Fig. 17 Installation of Superdeck in 1997 (photo: Creative Pultrusions)

Since 1999 Duraspan FRP decks have been installed in approximately 24 bridges in the USA. Installation of the Duraspan deck on a 25 m long (1.8 m girder spacing) bridge in New York in 2003 (Independence River bridge) is shown in Fig. 18.

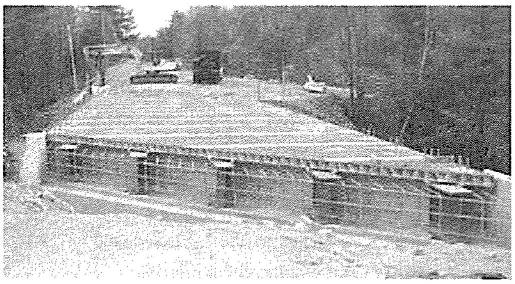

Fig. 18. Duraspan FRP deck panels (photo: Martin Marietta Composites)

FRP bridge deck panels weight approximately 100 kg/m$^2$ and currently cost about \$800/m$^2$. Typical FRP decks are between 150 and 225 mm deep and are glass-polyester or glass-vinylester FRP composites. Carbon fibers have not been used in decks due to cost concerns, although most deck designs are stiffness controlled. Most applications in the USA have been on steel-girder bridges, however, they have also been used on timber and prestressed concrete girder bridges. Installation of Duraspan FRP panels on prestressed concrete girders in 2001 on the Crow Creek bridge in Iowa is shown in Fig. 19.

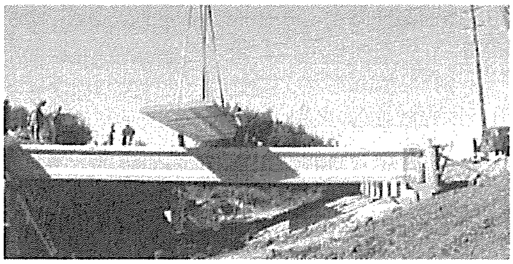

Fig. 19 Installation of FRP deck panels on PC girders (photo: Martin Marietta Composites)

The construction technology to install pultruded FRP decks is now fairly standard. The usual method is to bond 2.4 – 2.8 m wide panels together from individual pultruded multicelluar sections (approximately 600 – 800 mm wide) in the manufacturing plant. The individual pultruded profiles typically have tongue-and-groove type joints. These panels are then delivered to the site and lifted into place using cranes (as shown in Fig. 16.) They are then adhesively bonded and pulled together in the field using small portable jacks to achieve a good transverse joint. The panels are placed on built-up haunches (typically of steel angles or rigid polyurethane foam) and attached to the girders using grouted pockets with shear studs (or stirrups for PC girders) in a similar fashion to the technology used for precast concrete decks.

The surface of the FRP deck is typically covered with a wearing surface. Thin polymer concrete overlays are often used to reduce weight. Steel or concrete guardrails (barriers) can be attached pultruded FRP decks, either directly to the deck or to the exterior girders of the bridge. At this time, a standard, approved guardrail system for FRP decks does not yet exist and the guardrail system is usually approved on a case-by-case basis.

FRP girders and FRP decks have been developed using a combination of finite element methods, structural analysis models and most importantly small-scale and full-scale laboratory testing. Local buckling and crushing of the webs in FRP girders and in FRP decks is typically the critical failure mode under concentrated wheel loads[17,19,22]. In most applications FRP deck panels are intended to act in a non-composite fashion with the girders although composite action can be achieved with the appropriate pocket and shear stud detailing. Distribution factors for truck loads have been obtained using finite element models, and by conducting tests of the actual girders in place. It has been found that distribution factors for FRP girders using timber decks or steel girders using FRP decks are usually less than the AASHTO recommended distribution factors[11,16], however, AASHTO factors have typically been used in preliminary designs. At the present time there is no analysis and design procedure for the actual deck panels. The panels are specified in a performance-based fashion and the manufacturer provides assurance that the panel will work for the intended bridge spans and loading conditions. Acceptance criteria for FRP girders and FRP decks do not yet exist and each bridge is approached on a case-by-case basis.

## 4. Hybrid FRP and Concrete Highway Bridges

As an alternative to FRP only girders and FRP only decks there has been increasing interest in the USA in recent years to combine FRP materials with concrete to develop steel-free corrosion resistant highway bridges. The Texas U-beam described in 3(1) and shown in Fig. 11 is an example of one of these hybrid systems, where the FRP girder acts compositely with a concrete deck to form a hybrid system.

In 2001, a hybrid carbon shell (tube) girder developed at the University of California San Diego in the mid 1990s was used to support two 10 m long spans (2.4 m girder spacing) of the Kings Stormswater Channel Bridge on State Route 86 in Riverside County, California. An FRP Duraspan FRP pultruded deck with a 19 mm polymer concrete overlay was used on this bridge. In this system, shown in Fig. 20, the carbon tube is filled with concrete and acts as a stay-in-place (SIP) form and reinforcement[23].

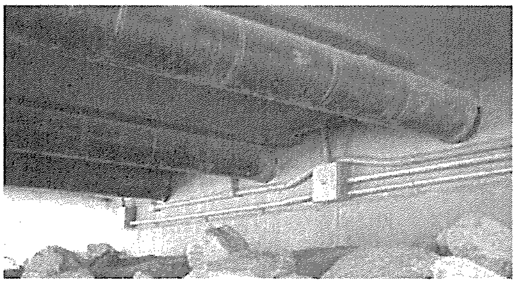

Fig. 20 Hybrid FRP tube/concrete girders in California

A glass-vinylester FRP SIP bridge deck formwork and bottom reinforcement panel developed by Composite Deck Solutions was used as one of the FRP systems in the Salem Avenue bridge deck replacement project in Ohio in 1999[16]. It was also used as part of the deck reinforcement system for a new prestressed concrete girder bridge having two 33 m spans (2.7 m girder spacing) constructed on State Highway 151 in Waupun, Wisconsin in 2003. Placement of the FRP SIP/reinforcement panel is shown in Fig. 21. The corrugated FRP panel was supported on variable height rigid polyurethane foam haunches. A pultruded grid was used as the top transverse reinforcement and pultruded FRP rebars were used as negative moment reinforcement over the pier in this hybrid system[24]. The FRP SIP panel cost \$231/m$^2$ (installed cost).

Fig. 21 FRP SIP/reinforcement panel being placed.

In 2004, a very-large, double-layer, glass-vinylester FRP grid reinforcing system was used in a 40 m long (2 m girder spacing) prestressed concrete girder bridge on State Highway 151 in Fond du Lac, Wisconsin. The pultruded grid reinforcement panels, shown in Fig. 22, were prefabricated to span the full 13.7 m width of the bridge for rapid, cost-effective, installation[25]. The FRP grid cost \$242/m$^2$ (installed cost).

Fig. 22 Installation of very large pultruded grids

## 5. Conclusions

The use of FRP composite materials in bridges in the USA has reached a level of technological maturity that is demonstrated by many applications having 10 or more years of service. FRP pedestrian bridges are cost-effective and can compete with traditional materials. FRP highway bridge components are significantly more costly than those of traditional materials. This, coupled with the lack of engineering design tools, is the largest impediment to widespread use of FRP materials in bridges.

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