International Symposium on Innovation &
Sustainability of Structures in Civil Engineering
Xiamen University, China, 2011

ADVANCED FIBER REINFORCED POLYMER COMPOSITES FOR SUSTAINABLE CIVIL INFRASTRUCTURES

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Abstract: Fiber reinforced polymer (FRP) composites are being promoted as the materials of 21st century because of their superior corrosion resistance, excellent thermo-mechanical properties, and high strength-to-weight ratio. For over 25 years, the Constructed Facilities Center at West Virginia University (CFC-WVU) has been conducting research on fundamentals of engineering and material sciences, innovation and development including field implementation of FRP composite components and systems for infrastructure applications with emphasis on the enhancement of performance, serviceability and durability over conventional materials. This paper will provide an overview on advanced FRP composites for: 1) highways and bridges including recent pre-fabricated pavement application, 2) utility poles, 3) pipelines, 4) renewable energy harvesting, 5) harsh environmental applications such as chimneys/flues, 6) rapidly deployable housing, 7) natural composites for green buildings, 8) decking for marine and naval structures, 9) advanced retrofitting, and 10) others. The Center has been involved in building a number of structures in the field using FRP composites. Those structures are being monitored for their structural response and durability and have been performing outstandingly, demonstrating remarkable advantages including cost effectiveness. Last, future research directions on materials for civil engineering innovation and structures are presented with emphasis on durability and sustainability.

Keywords: Fiber reinforced polymer, FRP, infrastructure application, durability, long term performance, cold water pipe, natural composites, green building, FRP wrap, fire performance, net-zero energy building, CICI

1 INTRODUCTION

Efficient infrastructure systems such as highways, bridges, buildings, pipelines, flood control systems (waterways) and utilities are all necessary for healthy economy and comfortable standard of living (Figure 1). Concrete and steel are the backbones of our current civil infrastructure. Timber, a natural composite, also plays a major role as a structural material in North America especially for residential construction. However, fiber reinforced polymer (FRP) composites (fibers, resins and additives) are just beginning to gain acceptability in civil infrastructure because of major research efforts initiated by the National Science Foundation of the United States of America (US-NSF) in 1980s.

The application of FRPs for civil infrastructure is resulting in a paradigm shift in material usage because FRPs provide favorable material properties (Figure 2). For example, FRPs provide nonmagnetic and noncorrosive products with higher strength to weight ratios than conventional materials. FRPs are also 'greener' in terms of embodied energy than concrete and steel. The use of FRP composites in civil infrastructure can improve innovation, increase productivity, enhance performance, and provide longer service lives, i.e. reduced life-cycle costs. Through proper selection of polymeric resin systems and reinforcements, FRPs can be tailor-made to meet certain strength and performance requirements.

Potential ease of application of FRP composites has led the academia and industry to focus their initial research and implementation in: 1) corrosion resistant reinforcing bars (rebar) for highways; 2) bridge decks and superstructures; 3) hazardous material containers susceptible to chemicals; 4) structures with longer spans (> 10,000 feet span) resulting in reduced self weight; 5) utility poles and towers; 6) strengthening and wrapping of in-service structures; and 7) many others, including cold water pipe for Ocean Thermal Energy Conversion project and composite deck houses for next generation navy battle ships.

Figure 1 Akashi-Kaikyo Bridge (photo courtesy of Wikipedia.org)

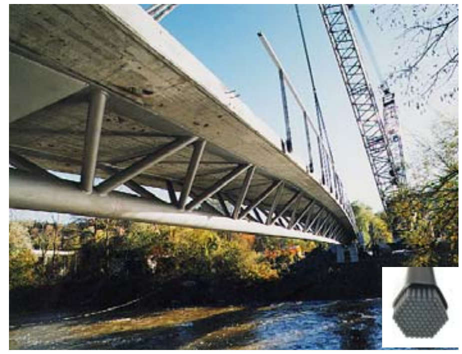

Figure 2 Kleine Emme Bridge, Switzerland, with CFRP cables in bottom chord (photo: Dr. Urs Meier)

The United States of America is not only the largest producer and user of FRP composites, but also leading the world's composites technology development and implementation for several decades. Such leadership is attributed to the major thrust provided by the US-NSF in cooperation with federal and state government agencies. About half of the global demand for FRPs resides in the US, accounting for about 4.2 billion lbs per year before recent economic downturn.

2 US-NSF SPONSORED I/UCRC- CICI: Center for Composites Infrastructure

The Constructed Facilities Center at West Virginia University (CFC-WVU) was established in 1980s to develop university-government-industry research cooperation, enhance knowledge base and emphasize field implementation. The Center's mission is to foster and conduct R & D vital to advancing new materials and new nondestructive evaluation (NDE) techniques and to promote and implement advanced FRP composites for civil infrastructures. CFC-WVU has been involved in advancing the development and production of FRP composites including their implementation for civil infrastructure applications such as highways, bridges and buildings. Many of the developed technological innovations and inventions (patents) through CFC-WVU have been implemented as a part of the transportation infrastructure (FHWA, 2001). CFC-WVU is recognized as a U.S. DOT/FHWA designated FRP Center of Excellence in 2000.

Although cost has traditionally been a major impediment to composites, advances in constituent material performance, manufacturing techniques, rehabilitation methods of in-service structures, structural optimization and rapid modular construction have recently lowered construction costs of composite-based infrastructure. For example, on a unit performance basis, CFC-WVU has been producing composites at lower costs than steel. FRP composites should have become the material of choice to revolutionize construction and rehabilitation of the United States' infrastructure. Yet composites have not been used extensively because of unavailability and non-familiarity with composite structural products.

Successful broadening of market application requires an industry-wide push and end user pull. Such an initiative must come about with support from all levels of composites manufacturing and construction industries. Along these lines CFC-WVU has been developing alliance with industry and end users since 2007 to improve FRP market penetration. In collaboration with Rutgers University (RU), North Carolina State University (NCSU), and University of Miami (UM) CFC-WVU has evolved into the National Science Foundation sponsored Industry/ University Collaborative Research Center (US-NSF I/UCRC), entitled "Center for Integration of Composites into Infrastructure (CICI)" in 2009. Currently, CICI has about 30 to 40 industry memberships and is playing a critical role in accelerating the adoption of polymer composites into infrastructure applications through industry-wide cooperation. More specifically the primary objective of CICI is to usher applications of composites in civil structures to the next level through: 1) long-term partnerships among industry, academe, and government, 2) promotion of research and development programs of mutual interest, and 3) enhancement of intellectual capability of the engineering workforce by integrating research and education. Educating policy makers from the government, industry and academia is also essential to quickly transform technological innovations generated to date into commercial products.

3 PRODUCTS AND APPLICATIONS

3.1 Highway and Transportation Structures

Advances in FRP composites have led to structural systems that allow for rapid deployment of bridge decks and other highway structures. The bridge structures under discussion include FRP bridge deck, stringer, beam, abutment panel, rebar, dowel bar and posts. Other FRP highway structures are signpost, signboard, guardrail system, sound barrier, drainage system (pipe, culvert), etc. Each of these products represents a high-volume market. Among the success stories of CFC-WVU researchers, a noteworthy one is the evolution of FRP decks through several design innovations over a period of 20 years, leading to a six-fold increase in ultimate strength and a three-fold decrease in unit cost of FRP bridge deck components. As a result of CFC-WVU patented designs coupled with Bedford Reinforced Plastics Inc.'s production and installation capability, lightweight 4" deep cellular FRP bridge decks are costing about $40/sq ft in 2006 (Figures 3 and 4). CFC-WVU has been working with WVDOT-DOH and other parties including private industries for over 20 years in promoting and implementing FRP composite products on West Virginia State Highway System. CFC-WVU helped WVDOH in building or rehabilitating 24 bridges with FRP composite materials in addition to using FRP dowel bars for pavements (FHWA, 2001). Figures 3 to 7 show some representative projects related to the use of FRP composite structures in highway infrastructure.

Fig 3 Goat Farm Bridge with FRP deck, Wirt County, WV

Fig 4 Pleasant Plain Road Bridge, Montgomery County, Ohio

Figure 5 Market Street Bridge (Wheeling, WV, built in 2000) with FRP decks

3.1.1 Newer Application- FRP Panel Pavement

The researchers at CFC-WVU have been developing, manufacturing, and evaluating FRP pavement panels. As a result, a section of Bakers Ridge Road near University High School, Morgantown, West Virginia, USA was the first to field-evaluate glass fiber reinforced composite panels for pavement applications (July 2009). Figure 8 shows the panel being installed (Figure 8a) and the finished pavement (Figure 8b).

Fig 6 Pavement with FRP Rebar, WV Route 9, Martinsburg, WV

Fig 7 Pavement with FRP Dowels Elkins Corridor H-Project, Elkins, WV

Figure 8 FRP modular panels for pavement project, before and after applying wearing surface

3.2 Utility Poles

Currently, there are 130 million utility poles in-service in the United States. Both new installation and replacement markets are about $4 billion per year (Hiel, 2001). Wood poles typically require treatment with environment-unfriendly preservatives to resist rot, decay, etc. in order to yield a service life of about 30-35 years. FRP poles (as shown in Figure 9) as one of three alternatives, i.e., steel, concrete and FRP composite, are beginning to penetrate into both the distribution and the transmission pole markets. FRP poles have advantages over steel poles in terms of non-conductive and non-corrosive properties, and over prestressed concrete pole in terms of lightweight, ease of installation and high ductility. Thus FRP poles have been receiving greater attention from electrical utility and telecommunication companies (Figure 9). CFC-WVU has collaborated with industry in design, manufacturing, testing and evaluation of FRP poles.

3.3 Pipelines

The pipeline infrastructure in the United States is extensive, including 161,189 miles of liquid fuel pipelines, 307,809 miles of natural gas transmission pipelines, 1,100,855 miles of natural gas distribution pipelines in service, and 1,500,000 miles of large water and sewage pipes (U.S. DOT Office of Pipeline Safety Statistics). The existing pipelines are predominantly made of steel, leading to corrosion problems. For example, September 9, 2010 San Bruno, CA, USA, the deadly pipeline accident killed at least 4 people, burned hundreds of homes, and caused hundreds of millions of dollars of damages which was attributed to corrosion in an aged natural gas pipeline system. In order to meet the increased demands, maintain safety and reliability, and be competitive, the pipeline industry is looking at alternatives including FRP to conventional steel pipe, for high pressure/ high volume natural gas transmission at reduced costs. FRP pipes have been widely accepted and implemented for sewage and sea-water applications as shown in Fig 10. Newly developed polyurethane-based high performance 16 inch diameter FRP pipe being tested at CFC-WVU Lab is shown in Figure 11 (2011).

Figure 9 FRP utility poles (photos courtesy of Duratel)

Figure 10 Sea water in-take pipes (www.reinforcedplastics.com)

Figure 11 A 16” diameter FRP pipe being tested at CFC-WVU Laboratory

3.4 Renewable Energy Harvesting Applications: Ocean Thermal Energy Conversion Cold Water Pipe

It is well known that composite application for turbine blades for wind energy is rapidly growing. The US has been leading the world with the most new installed wind energy capacity each year for the past several years. It is expected that the global wind power market will grow by over 155 percent to reach 240 GW of total installed capacity by 2012. Researchers in the United States are working towards producing quality blades at minimal cost to reduce power generation costs. Please refer to the paper by the authors (Liang and Hota, 2009).

For the past three years, U.S. Department of Energy (DOE) and Lockheed Martin have been collaborating to develop innovative technologies to enable ocean thermal energy power generation (PRNewswire, 2008). Ocean Thermal Energy Conversion (OTEC) uses the ocean's thermal gradient to drive a heat engine (Fig 12a). Since the ocean's temperature difference is relatively small, large volumes of seawater must be used to generate commercial levels of power. The fabrication and installation of large diameter cold water pipe that reaches depths of thousands of feet (~3000’) represents one of the largest technical challenges to the successful installation and operation of an offshore OTEC system. Figure 12 shows a section of 4m (13ft) in diameter FRP CWP at the Lockheed Martin facility while the goal is to manufacture 10m (33ft) in diameter pipe that will go 1000m (3300 ft) deep in the bottom of the ocean (Miller, 2011). On this project, CFC-WVU provides technical consultation and conducts testing and evaluation of composite materials and FRP CWP sections with emphasis on FRP durability and service-life prediction in seawater environment.

Figure 12 Ocean Thermal Energy Conversion Cold Water Pipe (Miller, 2011)

3.5 Harsh Environmental Applications

FRP has long been demonstrated with success for corrosive and harsh environmental applications such chemical storage and underground tanks. Another newer application is Chimneys/Flues. FRP composites as chimney liners in power plant smoke stacks make coal-fired power plants more efficient and environmentally friendly. Recently, International Chimney is installing the FRP liners at Fort Martin Power Plant near Morgantown, WV. The plant has a 60' diameter by 529' high reinforced concrete chimney that takes about two rows of 400' tall FRP liners that are 25' in diameter in addition to connection elbow. Each liner section is 25' in diameter and 31' high segment as shown in Figure 13 along with its connection elbow. Again, these applications are dealing with massive usage of FRP composites for large diameter FRP structures.

Figure 13 Large diameter FRP chimney flue liner, a) a module liner section and b) connection elbow (courtesy of International Chimney)

3.6 Modular Housing

Commercial and residential buildings are the basis of our social and economic infrastructure. Housing traditionally has been built from masonry, timber, steel and concrete. Fiber reinforced polymer (FRP) composites were initially used for small components, such as windows, canopies, doors, profiles, and other decorative features, but now for complete buildings. Dome-shaped FRP composite houses are readily available from market (CBS, 2009). Modular FRP houses have the following features: 1) no maintenance (no painting and do not deteriorate from weather, rot, or insect infestation); 2) lower heating and cooling cost (the modular FRP panels have built-in insulations and the dome shape further increases energy efficiency); 3) high structural strength (the curved surface of the panels reduces wind resistance, enabling the house to withstand hurricanes); 4) quick construction (modular design for ease of erection); 5) earthquake resistance (the FRP panels flex instead of breaking); 6) water resistance (completely sealed from the ground up); 7) portability (a FRP house can be easily disassembled and relocated to a new site). These buildings suit as disaster-resistant shelters, military barracks, school buildings, industrial factory and warehouse buildings, large dormitory settings for workers in remote locations, greenhouses, etc.

CFC-WVU designed, manufactured, and constructed the first FRP building in 1995 in collaboration with WV Department of Transportation (Figure 14). A recent inspection revealed that the building has been performing excellently for the past 16 years and looks new as shown in Figure 14. A newer modular unit is shown in Figure 15. Currently, CFC-WVU in collaboration with Quality Housing Inc. is developing FRP modular dwellings using natural composites integrated with many green concepts towards future sustainable buildings.

Figure 14 Multi-purpose FRP building, Weston, WV, constructed with modular FRP panels, Nov 1995 (photos taken on Aug 27, 2009)

Figure 15 FRP composite house being erected at BRP Inc. manufacturing facility (2008)

3.7 Composites Panels for Naval Platforms

CFC-WVU has also been advancing FRP composites for military infrastructural applications as illustrated in this section. FRP composites have proven history for water front applications as shown for marina decking (Figure 16). FRP in the form of panels, pipes, and posts, will find broad applications in every type of naval structures and shore facilities. For example, these applications can include: ship to shore bridges, fenders, docking systems, aircraft carrier decks, boat/ ship hulls, retaining walls, crosswalks, moorings, cables, piles, piers, underwater pipes, railings, ladders, and many others.

The Navy is currently expanding the use of composites in the first of a new family of advanced, multimission destroyers, the DDG-1000 *Zumwalt* class (LeGault, 2010). The DDG-1000 destroyer is designed to support both sea-based and land missions. It features a "tumblehome" wavepiercing hull and an uppersection deckhouse made predominantly of fiber-reinforced sandwich composite. Both the hull shape and composite deckhouse are intended to reduce the ship's radar cross-section and footprint. A photo and illustration showing all-composite deckhouse superstructure are shown in Figure 17. The all-composite superstructure not only reduces infrared and radar signatures but also reduce topside weight and total ship tonnage. CFC-WVU has been involved with the development of an automated pultrusion process for producing composite sandwich panels with improved mechanical performance and reduced production cost.

Figure 16 Marina with composite decking

Figure 17 DDG-1000 Zumwalt: Stealth warship (LeGault, 2010)

3.8 FRP Wraps

FRP retrofitting has been widely successfully used to strengthen the structures as an effective disaster prevention approach or to restore the damaged structures after disasters such as hurricane and earthquakes (see for example, Pang et al, 2011). In the United States, many of the existing highway or railroad bridges have either reached the end of their service life or require rehabilitation to continue in service. Due to decreased funding levels for new constructions, government agencies are interested in utilizing GFRP wraps to rehabilitate structures at a fraction of the outright replacement cost and extend the structural service life for few more decades. The advantages of FRP wraps include minimal traffic disruption, efficient labor utilization, ease of rehabilitation, optimization of load transfer, and cost effectiveness.

CFC-WVU has been actively involved with advanced FRP wrapping technology development, including specific design methods, material selection, field installation procedures, performance requirements and subsequent inspection techniques. Figure 18 is a group of photos showing how damaged piles of 11 timber railroad bridges on South Branch Valley Railroad (SBVR) lines in Moorefield, WV were rapidly rehabilitated and restored in-situ without affecting the rail traffic, with the use of Glass Fiber Reinforced Polymer (GFRP) composites (July 2010). These timber bridges consisted of total span lengths varying from 75 ft. to 1200 ft. with timber pile bents spaced 15-20 ft apart. The deteriorated piles were cracked, heart-rotted, and damaged to varying lengths. This rapid rehabilitation technique can be used on various other structural members including steel and reinforced concrete members in a highly cost effective manner to extend the service life of structural systems.

Figure 18 Retrofitting of railroad bridges using FRP wraps, SBVR, Moorefield, WV (July 2010)

4 DESIGN CODES

Construction industry relies on design codes, specifications and standards in order for any material to be used. The research advances thru various sponsored programs have directly resulted in development of FRP design codes and specifications. For example, the American Concrete Institute (ACI) and many federal and state government agencies have developed design and construction specifications for composite rebars for concrete structural elements and composite wraps to strengthen infrastructural systems (ACI 440.1R.03 & AASHTO LRFD Bridge Design Guide).

Recently, a new design code entitled, “Pre-standard for Load and Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures” has been developed through American Composites Manufacturers Association (ACMA) and the American Society of Civil Engineers (ASCE). This code will allow architects and structural engineers to incorporate FRP composite materials to build stronger, safer and better buildings. Advent of these codes will help FRP composites to compete on a level playing field with other construction materials like concrete, steel, wood and aluminum. Performance criteria for design, specification and installation will mean a higher degree of confidence for professional engineers and contractors to design and construct with FRP composites, in addition to instilling confidence in owners to field implement the advanced FRPs.

5 CURRENT AND FUTURE DIRECTIONS

With the world facing a crisis in terms of sustainable growth and environmental stability, the responsibility for change has fallen on to the entire engineering community. Green building movement, science in energy and environmental design, innovation for sustainability and many other programs are poised to steer the United States toward greener direction. We can envision an eco-urban habitat of zero carbon foot print. As a mid-term goal, research and development efforts on game changing technologies can aim at an urban habitat capable of breathing with ambient environment and minimizing energy and water usage. There are several projects being funded by NSF that focus on buildings of net-zero energy operation that maximize heating/ cooling/ lighting influence of solar energy and other natural resources to reduce energy consumption and yet maintain habitable conditions as well as buildings of net-zero water design. For example, green construction materials and methods will also be researched and field implemented to reduce embodied energy of these infrastructural systems. Living wall concept with flow channels and phase change materials is also being researched by a team at University of Colorado at Boulder. These topics will be further researched in-depth so that they can be economically implemented in field. With reference to FRP composites, durable, strong and stiff composite panels made of natural fibers and natural resins with ten times lower embodied energy than steel and four times lower cost needs to be developed and integrated with prefabricated modular sub-system design concept for zero construction waste.

The second important area is to continue to research in enhancing service life of infrastructure systems. Durability responses of composite materials and understanding the mechanisms that lead to the degradation of composites at micro- and macro-levels under the synergistic influence of hygro-chemo-thermo-mechanical loads become very important. Serviceability, durability, and cost-effectiveness are essential for wide spread use of any material. Long-term responses of composite structures under environmental loads including moisture exposure have to be established so that the accelerated aging test methodology (ATM) can be used to predict long-term performance of FRP composites thru life prediction models; thus more durable, efficient and safer FRP structures can be designed based on data collected using ATM and appropriate safety (knock-down) factors. These data have to be calibrated with field response data, monitored from the implementation works.

Another important area of research is on fire response of structural systems. The failure of any structural system under fire will be a thermal issue. In order to develop 100% fire resistant system, future studies with experimental and analytical approaches on the effects of “standard fire” (external heating) and “real fire” (open fire) exposure on structural systems have to be carried out. Topics may include: 1) formulation of thermal and structural performance criteria for structural materials based on dimensional/time relationships between full, intermediate and small scale specimens under fire; 2) fire performance (smoke and toxicity) experiments to evaluate the behavior of structural members of different scales with and without intumescents, insulation wraps, and other protective mechanisms including fire retardant admixtures; 3) development and validation of numerical models for predicting the fire performance of structural systems; 4) development of enhanced fire performance design equations and guidelines; and 5) retrofit of structural systems for better fire performance. In addition, future studies should include development of high temperature polymer resin systems to withstand up to 1500F.

Figure 19 Smart materials (Photos courtesy of Cornerstone Research Group, Inc.)

Furthermore, smart and multifunctional materials will be an important future focal area of FRP research (see for example, Figure 19). The topics of importance include: phase changing materials for energy storage and release, conductive polymers for solar cells, protective self-cleaning and de-polluting coatings, self-deicing materials, self-assessing and self-healing materials, coatings that can be used as sensors, and many others. For example, advances in the use of carbon fibers for sensing and detecting damage through polymers housed in nano-fibers will be heavily researched. Coatings consisting of nano-fibers can be used as sensors to detect micro-cracks, fire and hazardous chemicals. Electrically conductive coatings in conjunction with wireless networks will be developed to detect fire and other structural hazards.

6 CONCLUSIONS

Academia in cooperation with government and industry has made major strides in developing FRPs for infrastructure applications, including structures for highway and waterway, utility poles, wind turbine blades, and pipelines. These implementation efforts have been driven by recent market acceptance of composites, especially in highway construction. In the state of West Virginia alone, more than 30 highway bridges (see Figures 3 &5 for example) were built or rehabilitated with FRP composite materials. In addition, West Virginia Department of Transportation, Division of Highways is embarking on rehabilitating 400-500 concrete bridges using FRP composite wraps in the next 5 years (by 2016) because of their cost effectiveness and minimal user inconveniences.

Civil infrastructure industry has been poised for wider use of composites. For example, highway structures include not only FRP bridge decks, rebar and dowel bars, but also stringers, beams, abutment panels, signposts, signboard, guardrail systems, sound barriers, and drainage systems (pipe, culvert). Each of these products represents a multibillion potential market with longer service life. Similarly, implementation of FRP pipes (refer to Figure 11) for liquid fuel, gas, water and sewer transportation lead to a billion dollar annual market, while FRP pole potential market is of an order of 4 billion dollars per year. The utility pole and pipe industries are prone to use FRP composites more aggressively than before because of recent advances in strength by a factor of six and stiffness by a factor of two and half. Again, these advances have been made possible through NSF funding leading to novel manufacturing techniques integrated with material innovations and more efficient structural designs.

With recent launching of new design codes, new markets will open up and existing markets will broaden further for FRP composites industry. FRP composite materials will become an integral part of civil infrastructure, especially with reference to energy efficient modular housing using natural materials (Figure 15). Ultimately, the American public will benefit from the increased use of reliable and durable composite materials in terms of cost effectiveness and reduced user inconveniences due to ease of installation, low maintenance, longer service life, and greener products.

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