Subject Review

FIBER REINFORCED POLYMER COMPOSITES FOR BRIDGE STRUCTURES

Alexandra CANTORIU[1], *Florin EFTIMIE*[2]
[1] Military Technical Academy, e-mail: alexandra.cantoriu@gmail.com
[2] Military Technical Academy, e-mail: eftimieflorin@yahoo.com

ABSTRACT

Rapid advances in construction materials technology have led to the emergence of new materials with special properties, aiming at safety, economy and functionality of bridges structures. A class of structural materials which was originally developed many years ago, but recently caught the attention of engineers involved in the construction of bridges is fiber reinforced polymer composites. This paper provides an overview of fiber reinforced polymer composites used in bridge structures including types, properties, applications and future trends. The results of this study have revealed that this class of materials presents outstanding properties such as high specific strength, high fatigue and environmental resistance, lightweight, stiffness, magnetic transparency, highly cost-effective, and quick assembly, but in the same time high initial costs, lack of data on long-term field performance, low fire resistance. Fiber reinforced polymer composites were widely used in construction of different bridge structures such as: deck and tower, I-beams, tendons, cable stands and proved to be materials for future in this field.

Keywords: fiber reinforced polymer composites; type; properties; applications; bridge elements

REZUMAT

Progresele rapide în tehnologia materialelor de construcţii au dus la apariția unor noi materiale cu proprietăți aparte, urmărindu-se siguranța, economia şi funcționalitatea structurilor de poduri. O clasă de materiale structurale care a fost inițial dezvoltată cu mulți ani în urmă dar care a atras recent atenția inginerilor implicați în construcția de poduri este cea a compozitelor polimerice armate cu fibre. Această lucrare oferă o imagine de ansamblu asupra compozitelor polimerice armate cu fibre utilizate în construcția de poduri incluzând tipurile, proprietățile, aplicațiile şi viitoarele tendințe. Rezultatele acestui studiu au arătat că această clasă de materiale prezintă proprietăți remarcabile cum ar fi: rezistență specifică ridicată, rezistență la oboseală, rigiditate, transparență magnetică, greutate scăzută, se asamblează uşor şi sunt eficiente din punct de vedere a costurilor de întreținere dar în acelaşi timp au o rezistență scăzută la foc şi costuri inițiale ridicate. Compozitele polimerice armate cu fibre au fost utilizate pe scară largă în construcția diferitelor structuri ale podurilor, cum ar fi: punte, turn, tendoane şi s-au dovedit a fi materiale pentru viitor în acest domeniu.

Cuvinte cheie: compozite polimerice armate cu fibre, tipuri, proprietăți, aplicații, structuri ale podurilor

1. INTRODUCTION

Using fiber reinforced polymer (FRP) materials for rehabilitation of damage has been embraced around the world because of its lightweight, high strength, and corrosion resistance (Tavakkolizadeh and Saadatmanesh, 2003). Since conventional techniques for strengthening standard bridges are costly, time consuming and labor intensive they were developed many new ones that make FRP a much greater choice for repair and retrofit of different civil constructions. Fiber reinforced polymer composites are a combination of polymer resin (e.g., polyester, epoxy) as a matrix or binder, with strong rigid fiber assemblies (e.g. glass, carbon, aramid, boron) acting as the consolidation phase (Tuakta, 2005). The combination of the matrix phase with a reinforcing phase produces a new material with improved properties (e.g. resistance to abrasion, very high material toughness, anti-seismic behavior, electromagnetic neutrality, fatigue endurance) than the individual components (Stanley, 2005).

There are many different types of fibers that can be combined with various polymer matrix composites. The most common are fiberglass (S-glass, E-glass etc.) and carbon fibers (AS4, IM7 etc.). The choice of fibers for polymer matrix composites is determined by the application in which it is used. Fiber composites nowadays are being used in various applications from aerospace applications (for military aircraft: carbon fiber reinforced polymer (CFRP) fuselage and wings for F-35 Lightning II Joint Strike Fighter and, FRP entire structure of B2 stealth bomber, etc. for commercial aircraft: first airliner Boeing 787 with CFRP composite fuselage and continuous FRP metal-matrix composite B/Al tubular struts used as the frame and rib truss members in the mid fuselage section, etc. and as the landing gear drag link of the Space Shuttle Orbiter and Gr/Al composite antenna boom for the Hubble space telescope) (Ravikant et al., 2009-Suraj, 2001), civil infrastructure (I-beams, channel sections, prefabricated bridge decks etc.) (Ravikant et al., 2009), marine applications (FRP sluice gates, slide gates, stop gates, weir gates and flap gates, pipes, FRP composite-bearing piles, FRP blast gate dampers etc.) (Ronald, 2011), automotive (airport people mover with composite body, CFRP cockpit and aluminum space frame for BMW Megacity electric vehicle etc.) (Ronald, 2011) and to renewable energy generation (e.g. composite wind turbine blades) (Ronald, 2011). Fiber-reinforced polymer composites are increasingly being used in the construction of bridges and are being considered an alternative to concrete and steel.

The aim of this paper is to summarize, starting from a review of the available literature data, the main types de FRP, the main FRP characteristics (composition, mechanical properties, advantages and disadvantages) and their applications in the bridge construction. The study will try to answer the following questions: what types of FRP were used in making bridges? What are the properties of these fibers? What bridge structures can be made of FRP?

2. MATERIALS AND METHODS

A review of literature published between 2000 and 2012 on the FRP applications in bridge structure was performed. A rigorous search of major databases (including ScienceDirect, International Construction Database (ICONDA), and CSA) was conducted using specific keywords and phrases. Specific key phrase ”fiber reinforced polymer” combined with: „glass fibers”, „carbon fibers”, „plastic materials”, „characteristics”, „bridge”, „structures”, „applications”, „advantages”, „disadvantages” has been used in literature search. The relevant articles and abstracts that met the following criteria were selected for inclusion: (a) reviews, guidelines, research support studies of FRP applications and, (b) the characteristics and properties of FRP were reported. Letters and editorials were excluded and, also, papers published in a language other than English.

3. RESULTS AND DISCUSSIONS

Fiber reinforced polymer composites are increasingly being used in bridge structures for applications ranging from panel faces, tower, traverse and decks. Mainly three types of fiber reinforced polymers composites have been used until now in the bridge structures construction: FRP with carbon, FRP with glass and, FRP with aramid.

3.1. The use of fiber reinforced polymer composites with glass (GFRP) in the construction of bridge structures

Glass fiber reinforced plastics composites (GFRP) are considered an alternative to conventional materials for construction of some structural elements of the bridges due to their remarkable mechanical, physical and chemical properties. These materials are made by combining glass fibers (S-glass, E-glass, etc.) with diameters between 3 μm and 24 μm with thermosetting resins (polyester resins, epoxy resins and phenol resins). Basically, properties of GFRP depend on the properties of its components, the adhesion and mechanical compatibility between fiber and matrix and the angle between the fibers and loading (Potyrala, 2011). In recent years, due to the aging and deterioration of national highway bridge superstructures a major overhaul is required. Reinforcement corrosion was a major cause of the deficit superstructures. In this case, the excellent corrosion resistance and light weight of FRP make it potentially superior in long term performance to conventional reinforcing steel and, particularly in the case of GFRP (Mohammadali, 2011). Fiber glass made mainly of quartz and limestone powder is also considered to be environmentally friendly and their underlying resources are inexhaustible. Fiber glass/polyester requires for their manufacture 1/4 the energy needed for producing steel or 1/6 for aluminum (Potyrala, 2011).

GFRP was used most often as reinforcement in bridge structures constructed with concrete, but also for the complete components in bridges and, in particular for bridge decks (Table 1).

Table1. *GFRP bridge structures applications*

Matrix	Structural elements	Bridge	Additional Information	Ref.
isophaltic polyester resin	deck, tower, pylons	Aberfeldy Bridge (River Tay), Scotland	Rapid assembly made this bridge a very cost effective solution. It was designed with a live load capacity of 3.5 kN/m² but since then it had been strengthened to accommodate golf carts and it had been added ballast to improve its performance.	Potyrala, 2011; Stanley, 2005; Tuakta, 2005
thermoset resins	bars, panels	The Walters Street Bridge, Missouri	The Walters Street Bridge consists nine precast concrete bridge panels, each 0.30m deep reinforced FRP bars. The installation took place in 10 days (between June 18, 2001 and June 28, 2001).The laboratory test results show a good agreement between theoretical and experimental stiffness results.	Stone et al.,2001; Stone et al., 2002
-	honeycomb sandwich panels	St. Johns Street Bridge, Missouri	St. Johns Street Bridge is comprised of FRP decks supported by steel stringers and six lateral half-width panels. The installation took place in 10 days (between 25 September 2000 and 4 October 2000).The dead load of the bridge panels is 0.72 kN/m²	Stone et al., 2001
-	honeycomb sandwich panels	Jay Street Bridge, Missouri	Jay Street Bridge is comprised of FRP decks supported by steel stringers and four longitudinal panels. The installation took place in 10 days (between September 25, 2000 and October 4, 2000). The dead load of the bridge panels is 0.77 kN/m².	Stone et al., 2002
-	honeycomb sandwich panels, slab bridge	St. Francis Street Bridge, Missouri	This is a prefabricated FRP slab bridge, composed exclusively of four FRP panels, each 600.1 mm thick. The installation took place in 5 days (between November 13, 2000 and November 17, 2000). The dead load of the bridge panels is 1.72kN/m². Failure of the first beam was observed at approximately 864.7kN.The maximum bottom fiber stress at failure was 30% higher than the design failure limit.	Stone et al., 2001
epoxy resin	deck	Bonds Mill Lift Bridge, England	Bonds Mill Bridge is an electrically operated lift bridge. Composite materials were used because of lightweight structure.	Stanley, 2005

Matrix	Structural elements	Bridge	Additional Information	Ref.
thermosetting polyester vinyl ester resin	deck	Troutville Weigh Station Bridge, Virginia	A data acquisition monitoring system to collect and report real data has been installed with the purpose of constructing future experimental bridge decks.	
epoxy polymer	deck, square tubes	Laurel Run Road Bridge, Pennsylvania	-	Stanley, 2005
polyester polymer concrete overlay	deck, piles, I-beams	Laurel Lick Bridge, West Virginia	-	Stanley, 2005
thermosetting resins	girders, sandwich deck	Tech 21 (Smith Road) Bridge, Ohio	Materials used at this bridge provide high specific strength, specific stiffness, and corrosion resistance. Health monitoring instrumentation was installed for the purpose of providing information on the performance under field conditions. Special sensors have been embedded and linked to special computers designed for continuous monitoring.	Stanley, 2005

As we can see in Table 1 polymer composites reinforced with glass fibers are used mainly to decks, panels, pylons, girders and tubes. Because of GFRP low weight, the installation of bridges (e.g. The Walters Street Bridge, St. Johns Street Bridge, Jay Street Bridge and St. Francis Street Bridge at (Stone at al., 2001)) took place between five to ten days which offers the advantages of not interrupting the traffic circulation and provides a very cost effective solution. For continuous monitoring of bridge performance under field conditions were incorporated special sensors that are connected to computers specially designed for data storage (e.g. Tech 21 Bridge, Ohio and Troutville Weigh Station Bridge, Virginia at (Stanley, 2005)). The polymeric composites reinforced with glass fibers have been shown thus to have a high specific strength, high specific stiffness and a remarkable corrosion resistance which makes them a good choice for bridge structures.

3.2. The use of fiber reinforced polymer composites with carbon (CFRP) in the structural components of bridges

Polymer composites reinforced with carbon fibers (CFRP) continue to play an important role among the new structural materials on solving the persistent problems that arise in applications due to its properties (e.g. high specific stiffness, high specific strength, high corrosion resistance, light weight, and durability) (Amjad and Gordon, 2009). These materials are made by combining carbon fibers (AS4, IM7, etc.), which are a type of high performance fibers, weighing approximately 50% of the original fibers with thermosetting resin (e.g. epoxy resin, vinyl ester resin) (Potyrala, 2011). The composites reinforced with carbon fibers have a higher tensile strength than other materials (therefore is used in elements carrying tensile forces). The value of Young's modulus of CFRP composites is comparable to modulus of steel, that has a density over five times larger (Potyrala, 2011). Carbon fiber reinforced polymers in form of wires are materials with remarkable properties for stay cables or tendons, such as: high tensile strength, high fatigue resistance as well as low weight and excellent chemical resistance. To protect the CFRP cables from the destructive effects of UV radiation, wind and moisture it is used a polyethylene tube (Potyrala, 2011).

Carbon fiber reinforced with polymer matrix composites are widely applicable in various important structural components of bridge (e.g. deck, tubes, double web beams) as it can be seen below (Table 2).

Table2. *CFRP bridge structures applications*

Matrix	Structural elements	Bridge	Additional Information	Ref.
vinyl ester resin	deck, tubes	All FRP bridge deck installed on the campus of University of Missouri	To observe the behavior of the bridge during its service life, fiber optic sensors are installed. FRP bridge deck is a good alternative for conventional short-span bridges was demonstrated during the performed tests.	Tuakta, 2005
-	deck	Brown School Road, Boone Country, Missouri	The deflection of the mid span is reduced by approximately 20% after strengthening with CFRP composites that contributes on the stiffness of the structure.	Tarek et al. 2001
-	deck	Creasy Springs, Boone Country, Missouri	The deflection of the mid span is reduced by approximately 13% after strengthening with CFRP composites.	Tarek et al. 2001
-	deck	Coasts Lane, Boone Country, Missouri	There was no required flexural strengthening but it was added to ensure comparable reserve strength with CFRP materials.	Tarek et al. 2001
vinyl ester resin	double web beams	Route 601 Bridge, Sugar Grove, Virginia	The Rt. 601 Bridge was instrumented with strain gauges and deflectometers to monitor its behavior during load testing. The same instrumentation plan was used for the October 2001 load test and the June 2002 load test.	Edgar, 2002
vinyl ester resin	double web beams	Tom's Creek Bridge, Blacksburg, Virginia	An AASHTO standard specification criterion for an all timber bridge is corresponding with the maximum deflection of 11 millimeters which was resulted from the tests loads.	Edgar, 2002
-	plates	Hythe Bridge, Oxford	For removing the tensile stress from the cast beams, the bridge was subjected to a load of 40 tones. After multiple tests CFRP laminates showed outstanding properties such as high tensile modulus and high tensile strength.	Hakan, 2003

As the Table 2 shows, two bridges (Brown School Road Bridge and Creasy Springs Bridge Missouri) that have incorporated into their structures a deck, under the strengthening with CFRP composites revealed a deflection reduced by 20% and 13% (Tarek et al.). The behavior of the bridge during its service life can be observed by using fiber optic sensors installed on CFRP bridge deck as reported Tuakta et al., about the all existing CFRP bridge deck on the campus of University of Missouri. Another CFRP element used in the construction of bridges is CFRP double web beams that are incorporated in Route 601 Bridge and Tom's Creek Bridge, Virginia (Edgar, 2002). The Route 601 Bridge is also closely monitored by optical sensors to determine its behavior in nature.

All these results highlight the role of the CFRP materials in construction of different bridge structure based on their remarkable properties such as high tensile modulus and high tensile strength.

3.3. The use of fiber reinforced polymer composites with aramid (AFRP) in the bridge construction

A combination of engineering, fundamental science and research applications led to the development of aramids (aromatic polyamides) in DuPont Industrial Corporation (Bhattacharyya and Fakirov). The property that makes polymers reinforced with aramid fibers to be distinguished from polymers reinforced with glass or carbon is the cost-effective performance at reduced weight. Composites reinforced with aramid fibers have a remarkable impact resistance due to its high strength, low density and high elongation (Bhattacharyya and Fakirov). Aramid fiber composites nowadays are being used in various applications from aerospace industry (storage bins, air ducts, honeycomb structures, etc.) and sporting goods (hockey shafts, golf club shafts, fishing rods, and tennis rackets, etc.) to naval applications (e.g. boat fuselages) (Bhattacharyya and Fakirov). Fraction of the fiber constituent in FRP is quite high, usually well above 30% by volume and it is primarily influenced by the properties of the aramid reinforcing fibers. Polymeric composites containing aramid fibers developed economic building material for bridge structures. Thus, Aberfeldy Bridge crossing the River Tay, Scotland made from GFRP cross beams connected to stay cables and deck, attached to the 40 Parafil-Kevlar aramid fibers cable isolated in a low density polyethylene layer of protection, and then put in place across the river as reported by (Potyrala, 2011; Stanley, 2005; Tuakta, 2005). Other bridges were the AFRP were used in some structure are Sumitomo Bridges, Japan (Oyama, 1998) and M-15 over Gooding Creek Bridge, Michigan (Amy, 2005). The Sumitomo Bridges are two parallel bridges built using aramid fiber and vinyl ester resin designed for 20 tones truck loads. The bridge girders were in two layers with 12 aramid fiber reinforced tendons at the bottom and 4 post tensioned tendons at the top.

4. CONCLUSIONS

The high fatigue resistance, high strength, low density, lightweight, corrosion resistance and a very low coefficient of thermal expansion in the fiber orientation makes fibers reinforced polymer composites highly desirable for applications of bridge structures. Carbon fiber reinforced with polymer matrix composites having a higher tensile strength than other materials can be used in elements carrying tensile forces such as: cable and tendon systems, deck, tubes and double web beams. Glass fiber reinforced polymer composites have proved to be an excellent choice for rehabilitation of national highway bridge superstructures due to its excellent properties such as high corrosion resistance and light weight. This type of fibers has been applied to the deck, tower and piers. The deficiencies of glass fibers reinforced polymers are related to poor fatigue resistance and moisture absorption that may affect the resin and allow the alkali to degrade the fibers. Excellent properties regarding strength, low density and high elongation of aramid fiber reinforced polymer composites make that the main applications are found in aerospace, sporting goods and the naval industry. In terms of its applications in the construction sector of bridges, these are limited to cables and tendons.

Future research is needed to develop the most effective and durable resin formulations that will make the use of fiber composites more cost effective than conventional materials for bridge structures.

Given the remarkable properties of these types of materials, multiple studies will continue with the desire to achieve efficient bridge structures.

In conclusion, due to their outstanding properties and its superior advantages compared to those of traditional materials, fiber reinforced polymer composites are considered to be materials for future in the bridge construction.

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