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Innovative Field Applications of Fiber Reinforced Polymer Composite Reinforcing Bars in Civil Engineering Infrastructures

Hamdy M. Mohamed*

Applied Science University, Kingdom of Bahrain

E-mail: hamdy.mohamed@asu.edu.bh

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Abstract: In the last decade, there has been a rapid increase in using noncorrosive fibre-reinforced polymers (FRP) reinforcing composite bars for concrete structures due to enhanced properties and cost-effectiveness. The FRP bars have been used extensively in different applications such as bridges, parking garages, tunnels and marine structures in which the corrosion of steel reinforcement has typically led to significant deterioration and rehabilitation needs. Many significant developments from the manufacturer, various researchers and Design Codes along with numerous successful installations have led to a much higher comfort level and exponential use with designers and owners. After years of investigation and implementations, public agencies and regulatory authorities in North America has now included FRP as a premium corrosion resistant reinforcing material in its corrosion protection policy. This paper presents a summary and overview of different recent field applications of FRP bars in different types of civil engineering concrete infrastructures.

Keywords: innovation, reinforced polymer, reinforced bars, fiber, civil engineering, applications.

1 Introduction

Electrochemical corrosion of steel is a major cause of the deterioration of the civil engineering infrastructure. It is becoming a principal challenge for the construction industry world-wide. An effective solution to this problem is the use of corrosion resistant materials, such as high-performance fibre-reinforced polymer (FRP) composites, (Benmokrane et al. 2002; Mohamed & Benmokrane 2014). The applications of FRP reinforcements in the last 10 years have been approved that the cutting-edge technology has emerged as one of the most cost-effective alternative solutions compared to the traditional solutions. The use of concrete structures reinforced with FRP composite materials has been growing to overcome the common problems caused by corrosion of steel reinforcement. The climatic conditions where large amounts of salts are used for ice removal during winter months may contribute to accelerating the corrosion process. These conditions normally accelerate the need for costly repairs and may lead to catastrophic failure.
Known to be corrosion resistant, FRP bars provide a great alternative to steel reinforcement. FRP materials in general offer many advantages over the conventional steel, including one quarter to one fifth the density of steel, no corrosion even in harsh chemical environments, neutrality to electrical and magnetic disturbances, and greater tensile strength than steel (Benmokrane et al. 2006; 2007).
The objective of this paper is to show that FRP bar is on its way toward gaining widespread acceptance in worldwide. Clearly, the most tangible successes are in the area of highway reinforced concrete bridges, tunneling, water tank, and concrete pavement in which the corrosion resistance of FRP reinforcements as well as their installation flexibility are taken advantage of. In the following sections, development of codes and guidelines, recent field applications of FRP bars in bridges, tunnels, and water storage tank are presented.

2 Design Codes and Guidelines

* Corresponding author E-mail : hamdy.mohamed@asu.edu.bh

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A number of committees from professional organizations around the world have addressed the use of FRP bars in civil structures. These have published several guidelines and/or standards relevant to FRP as primary reinforcement for structural concrete. The recommendations ruling the design of FRP RC structures currently available are mainly given in the form of modifications to existing steel RC codes of practice, which predominantly use the limit state design approach. Such modifications consist of basic principles, strongly influenced by the mechanical properties of FRP reinforcement, and empirical equations based on experimental investigations on FRP RC elements.

In North American, several codes and design guidelines for concrete structures reinforced with FRP bars have been published from 2000 to 2014. In 2000, the Canadian Highway Bridge Design Code (CHBDC) [CAN/CSAS6-00, (CSA 2000)] has been introduced including Section 16 on using FRP composite bars as reinforcement for concrete bridges (slabs, girders, and barrier walls). Design manual (ISIS-M03-2001) for reinforcing concrete structures with FRP was presented by the Canadian Network of Centres of Excellence on Intelligent Sensing for Innovative Structures (ISIS). In 2002, CAN/CSA-S806-02 has been published by the Canadian Standards Association (CSA 2002) for design and construction of building components with FRP bars.

The American Concrete Institute (ACI) introduced the first, second and third guideline (ACI 440.1R) for the design and construction of concrete reinforced with FRP bars in 2001, 2003 and 2006, respectively. The ACI 440.1R design guidelines are primarily based on modifications of the ACI-318 steel code of practice (ACI 318-02, 2002).As a result of the valuable, enormous and great research efforts on different types of FRP-reinforced concrete structures in worldwide during the last decade, the aforesaid North American codes and design guidelines have been updated and modified to encourage the construction industry to use FRP materials [CAN/CSAS6-14; CAN/CSA-S806-12; ACI 440.1R-15].

Nowadays, the CAN/CSA-S806-12 (2012) is the most recently issued Canadian guidelines on the design and construction of building components with FRP. The CSA S806 has been completely revised. Many of its provisions have been improved based on the latest research results and experience in the field. The CSA S806-12 contains new provisions on: punching shear at slab-column connections with or without moment transfer, confinement of columns by FRP internal ties or hoops, design of FRP reinforced member for combined effects of shear, torsion and bending, reinforcement development length and detailing, strut and tie model for deep beams, corbels and brackets, shear strengthening of reinforced concrete members by externally bonded reinforcement, and FRP retrofit of reinforced concrete members for enhanced seismic resistance. The new standard covers all the basic design requirements for FRP reinforced and retrofitted structures.

In addition to the design of concrete elements reinforced or prestressed with FRP, the guidelines also include information about characterization tests for FRP internal reinforcement. As for the predominant mode of failure, the CSA S806-12 remarks that “all FRP reinforced concrete sections shall be designed in such a way that failure of the section is initiated by crushing of the concrete in the compression zone”. In this code, new design equations are included for design punching shear capacity of FRP-RC flat slab. Also, it is of interest to mention that this code permits of using FRP bars in columns and compression members.

In order to establish stringent guidelines and values for FRP manufacturers and quality control mechanisms for owners to ensure a high comfort level of product supplied, ISIS Canada together with the manufacturer had initiated the “Specifications for product certification of FRP’s as internal reinforcement in concrete structures”. (ISIS Canada Corporation 2006) This document was the basis for the new Standard CSA S-807-10 on Specification for Fibre Reinforced Polymer (FRP). This Standard covers the manufacturing process requirements of fibre-reinforced polymer (FRP) bars or bars that are part of a grid for use in non-prestressed internal reinforcement of concrete components of structures (e.g., bridges, buildings, and marine structures). The FRP bars are classified on the basis of their fibres, strength, stiffness, and durability. Only FRP bars made with aramid, carbon, or glass fibres are considered in this Standard.

3 FRP Composite REINFORCING bars

3.1 Advantages

The technology of reinforced concrete is facing a serious degradation problem in structures due to the corrosion of steel bars. In North America, the repair costs are estimated to be close to 300 billion dollars. Several options have been explored, most notably the use of galvanized steel rebar, epoxy coated or stainless steel. The results, however, have been disappointing as these solutions have turned out to be less than effective or cost prohibitive. The FRP bars have proven to be the solution. Lightweight, corrosion resistant, and offering excellent tensile strength and high mechanical performance, FRP bar is installed much like steel rebar, but with fewer handling and storage problems. The material cost might still be higher compared to the costs of conventional steel products, but this fact is more than compensated with the lesser maintenance work involved during the lifetime of the structure. Also, the weight of a FRP bar is only a fourth of its steel counterpart, having the same dimensions. Combined with the flexibility of the bars this allows an easy installation even in confined working space or where the support of lifting equipment is not available. The most commonly manufactured fibers employ

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glass and carbon. E-glass is the most common fiber because of its strength and resistance to water degradation. It is also used as an electrical insulator.
On the technical level, FRP products have important advantages. FRP reinforcement bars can be used in tunnel application as soft-eyes have a very high tensile strength which can reach far over 1200 N/mm2. Besides flexibility, elasticity and the minimal environmental impact the GFRP bars can be cut with working tools like saws, pilling/drilling equipment and TBM tools. This avoids damages to cutter heads and does not delay the work progress as piling or cutting through GFRP bars is unproblematic. The fiber bars are split in small pieces which do not harm slurry pipes.

3.2 Mechanical Properties

The mechanical properties of FRP bars are typically quite different from those of steel bars and depend mainly on both matrix and fibers type, as well as on their volume fraction, but generally FRP bars have lower weight, lower Young's modulus but higher strength than steel. The most commonly available fiber types are the carbon (CFRP), the glass (GFRP) and the aramid (AFRP) fibers. Table 1 gives the most common tensile properties of reinforcing bars, in compliance with the values reported by CSA S-807-10.

Table 1: Typical Mechanical Properties of GFRP Bars.

Grade	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Ultimate Tensile Strain
I	588 - 804	40 - 47	0.0134 – 0.0189
II	703 - 938	50 - 59	0.0133 – 0.0179
III	1000 - 1372	60 - 69	0.151 – 0.0211

4 Recent FRP Field Applications

4.1 Water Tank

Reinforced concrete (RC) tanks have been used for water and wastewater storage and treatment for decades. Design of these tanks requires attention not only to strength requirements, but also to crack control and durability. RC water treatment plant structures are subject to severely corrosive environments as a result of using the chlorine to treat the wastewater before it is released. So, the challenge for the structural engineer and municipalities is to design these structures using noncorrosive fibre-reinforced polymers (FRP) reinforcing bars. The first worldwide concrete chlorination water treatment tank totally reinforced with FRP bars was designed in 2010 and the construction started and finished in 2012. The project is located in Thetford Mines city, Quebec, Canada and it is considered as one component of water treatment plant for municipality. The volume capacity of the tank is 4500 m3, and it has the dimensions 30.0 m wide, 30.0 m length and 5.0 m wall height. The structural system of the tank is rectangular under-ground tank resisted on raft foundation that supports the vertical walls and top slab. The design of the tank was made according to CAN/CSA-S806-02, Design and Construction of Building Components with Fibre-Reinforced-Polymers. This included the use of High Modulus GFRP reinforcing bars (Grade III, CSA S807) as main reinforcement for the foundation, walls and top slab. The tank is well instrumented at critical locations for strain data collection with fiber-optic sensors. Figure 1 shows the FRP bar reinforcements in the vertical walls and overview of the complemented FRP tank. The field test results under actual service conditions for the strain behavior in the FRP bars at different location in the tank are indicated a significant value less the 1.0 % of the ultimate strain. In conclusion, the construction procedure, serviceability performance under real service conditions (water and earth pressure), and monitoring results of the FRP-reinforced walls and slabs of the tank, in terms of strain, cracking and deflection were very conservative and satisfactory when compared with the serviceability requirements and strength needed.

4.2 Highway Bridge Structures

Corrosion of steel reinforcing bars stands out as a significant factor limiting the life expectancy of reinforced concrete infrastructure worldwide. In North America in particular, the corrosion of steel reinforcement in concrete bridges subjected to deicing salts and/or aggressive environments constitutes the major cause of structure deterioration, leading to costly repairs and rehabilitation as well as a significant reduction in service life. According to the 2013 Report Card for America's Infrastructure findings, ASCE, nearly one-tenth of the 607,380 bridges in the National Bridge Inventory were classified as structurally deficient. Of this total, over 235,000 are conventional reinforced concrete and 108,000 were built with

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Fig. 1: FRP-reinforced concrete tank, Qc, Canada.

prestressed concrete (NACE International). The report further states that $76 billion are needed for deficient bridges across the United States for maintenance and capital costs for concrete bridge decks and for their concrete substructures. In addition, the United States Federal Highway Administration (FHWA) estimates that eliminating the nation's bridge deficient backlog by 2028 would require an investment of $20.5 billion annually because of corroded steel and steel reinforcement. The report also states that "the nation's 66,749 structurally deficient bridges make up one-third of the total bridge decking area in the United States, showing that those bridges that remain classified as structurally deficient are significant in size and length, while the bridges that are being repaired are smaller in scale." Problems related to expansive corrosion could be resolved by protecting the steel reinforcing bars from corrosion-causing agents or by using noncorrosive materials such as fiber-reinforced-polymer (FRP) bars. Therefore, since the late 1990s, the Structures Division of the MT at different provinces has been interested in building more durable bridges with an extended service life of 75–150 years. For example, the MT at Québec (MTQ), Canada has carried out, in collaboration with the University of Sherbrooke, (Sherbrooke, Québec), several research projects utilizing the straight and bent non-corrodible FRP rebar in concrete deck slabs and bridge barriers (Mohamed et al. 2014; Ahmed et al. 2014; Mohamed and Benmokrane 2014). The use of FRP bars as reinforcement for concrete bridge provides a potential for increased service life and economic and environmental benefits.

In the last ten years, the FRP bars have been used successfully in hundreds bridge structures across Canada and USA, see Figure 2. These bridges were designed using the Canadian Highway Bridge Design Code or the AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings. Straight and bent FRP bars (carbon or glass) were used mainly as internal reinforcement for the deck slab and/or for the concrete barriers and girders of these bridges. In general, all the bridges that included with FRP reinforcements though the ten years ago are girder-type with main girders made of either steel or prestressed concrete. The main girders are simply supported over spans ranging from 20.0 to 90.0 m. The deck is a 200 to 260 mm thickness concrete slab continuous over spans of 2.30 to 4.0 m. Most of these bridges have been reinforced with the glass FRP bars as a result of their relatively low cost compared to other types of FRPs (carbon and aramid). The FRP bars were used mainly as reinforcement to the deck slabs, barriers and girders.

Fig. 2: FRP decks/app slabs/ barriers, Skagit River – BC MOT (2009).

Recently, the GFRP bars have been used as the main reinforcement in the deck slab of cable stayed bridges, Nipigon River Bridge, ON, Canada. The Nipigon River Bridge spans the Nipigon River in Nipigon, Ontario on Highway 11/17. A new four lane cable stayed bridge is replacing the old two lanes, four span plate girder structures. The new bridge includes cable-supported spans of 112.8 m and 139 m. The 36.2 m wide deck is comprised of concrete deck panels totally reinforced with GFRP bars and supported on transverse steel beams, see Figure 3. The objectives were to implement FRP

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bars in RC cable stayed bridge to overcome the steel expansive-corrosion issues and related deterioration problems; to assess the in-service performance of the FRP-RC bridge deck slab after several years of operation; and to design durable and maintenance-free concrete for cable stayed bridge. The deck slab was design to sustain significant axial compression force resulted from the cables and bending moment as resulted from the live and dead loads (Mohamed & Benmokrane 2012).

Fig. 3: Cable stayed bridge, Nipigon River Bridge, ON (2015).

4.3 GFRP Soft Eyes in Tunnels

Building tunnels with Tunnel Boring Machines (TBM) is today state of the art in different ground conditions. Launching and receiving the TBM in shafts and station boxes has in earlier years required a considerable construction effort. Breaking through the steel reinforced walls of the excavation shaft with a TBM required extensive measurements and preparation works, (Mohamed and Benmokrane 2015; Schürch and Jost 2006). FRP is an anisotropic composite material with a high tensile strength in axial direction and a high resistance against corrosion.

The anisotropy of the material is quite advantageous at excavation pits for the starting and finishing processes at automated excavation like tunnel boring machine (TBM) and Pipe jacking. Therefore, using FRP bars in reinforced walls and piles of the excavation shaft allows the designer and contractor today to find innovative solutions for the well-known situation and save time and costs on site. Soft-Eyes consist usually of bore piles or diaphragm walls which are locally reinforced with GFRP bars and stirrups. The sections below and above the tunnel opining are reinforced steel bars. Depending on the designer and contractors preferences full rectangular sections are built out of GFRP bars or the fibre reinforcement follows more closely the tunnel section resulting in a circular arrangement of the GFRP links and similar adjustments for the vertical bars. Building the corresponding reinforcement cages out of GFRP bars on site requires the same working procedures as for an equal steel cage. Recently, GFRP bars have been used in different tunnel projects in Canada (South Tunnels, Keele Station, Hwy 407 Station-TTC Subway North Tunnels and Eglinton Crosstown LRT: Toronto, ON). Whereas, GFRP bars were used to reinforce GFRP cages up to 19.0 m long (diameters ranged from 600 to 1100 mm). Highest grade 60 GPa 32.0 m vertical bars were used with #5 (16.0 m) 50 GPa continuous spirals with 150 mm pitch, see Figure 4 (Mohamed & Benmokrane 2015).

Fig. 4: Handling and lifting the GFRP Soft-Eyes.

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4.4 Continuously Reinforced Concrete Pavement with GFRP Bars

Continuously reinforced-concrete-pavement (CRCP) designs are premium pavement designs often used for heavily trafficked roadways and urban corridors. Although CRCP typically is an effective, long-lasting pavement design, it can develop performance problems when the aggregate–interlock load transfer at the transverse cracks has degraded. The prevalence of wide cracks in CRCP has frequently been associated with ruptured steel reinforcement and significant levels of corrosion. This has generated recent interest in identifying new reinforcing materials that can prevent or minimize corrosion-related issues in CRCP. Glass-fiber-reinforced-polymer (GFRP) bars are one product being investigated for use in CRCP instead of conventional steel bars.

Since the early 1990s, the Ministry of Transportation of Quebec (MTQ) has renewed emphasis on building long-lasting concrete pavements suited to local traffic and climatic conditions. In 2000, these efforts led to the construction of Canada's first roadway with continuously reinforced concrete pavement (CRCP). Five years later, however, concerns were raised about the long-term performance of CRCP, as portions of this initial installation were found to have insufficient cover over the bars and core samples showed that the longitudinal reinforcement was corroding at transverse cracks (Thébeau 2006). These observations, coupled with the knowledge that up to 60 tonnes (65 tons) of salt per year can be spread on a 1 km (0.6 mile) long stretch of a two-lane pavement in Montréal (nearly three times the amount of salt used on roads in the State of Illinois), led the MTQ to select galvanized steel as the standard reinforcement for subsequent CRCP projects and to continue investigating other systems with enhanced corrosion resistance. As part of these investigations, the MTQ and the University of Sherbrooke has been studying the use of glass-fiber-reinforced-polymer (GFRP) bars for CRCP since 2006. In September 2006, a 150 m long section of eastbound Highway 40 (Montréal) was selected as a demonstration project (Benmokrane et al. 2008), see Figure 5. Through the initial 18 months of pavement life, the maximum measured strain value in the reinforcement was 0.0041. This is within the design limit recommended in ACI 440.1R-06.

Fig. 5: GFRP bar placement in center lane in Highway 40 (Montréal)-2013.

5 Conclusions

The observations and the outcomes from the different field applications reported in this paper can be summarised into the following: corrosion resistance is without a doubt the main motive and attraction to use FRP over steel. Application of FRP reinforcement in different structures has been proved to be very successful to date. From the construction point of view it was felt by the construction personnel that the lightweight of the FRP reinforcements were easy to handle and place during construction. Concrete bridges, water tank, soft eye-tunnel application, and continuously reinforced-concrete-pavement provide an excellent application for the use of FRP in new construction.

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