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Recent Developments of FRP Bars as Internal Reinforcement in Concrete Structures & Field Applications

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ABSTRACT

In the last decade, there has been a rapid increase in using noncorrosive fibre-reinforced polymers (FRP) reinforcing 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, water tanks, tunnels and marine structures in which the corrosion of steel reinforcement has typically led to significant deterioration and rehabilitation needs. Significant developments from the manufacturers, researchers and Design Standards along with numerous successful installations provided designers and owners with a high comfort level and led to an exponentially increasing use. After years of investigation and implementation, public agencies and regulatory authorities in North America have now included FRP as a premium corrosion resistant reinforcing material in their corrosion protection policies. Currently, AASHTO LRFD Bridge Design Specifications and the Canadian Highway Bridge Design Code (CHBDC) contain design provisions for the design of concrete bridge members reinforced with FRP bars. As a result, well over 500 bridges across Canada and USA have been designed and constructed using FRP bars. This paper presents a summary and overview of different recent field applications of FRP bars in different types of civil engineering concrete infrastructures.

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. 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 need costly repairs as they may lead to catastrophic failure. An effective solution to this problem is the use of corrosion resistant materials, such as high-performance fibre-reinforced polymer (FRP) composites. The use of FRP reinforcements in the last 10 years has approved this cutting-edge technology 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 main objective of this paper is to show that FRP bar is on its way towards gaining widespread worldwide. The most tangible successes are in the area of highway bridges, parking garages, tunneling and marine structures in which the corrosion resistance of FRP bars 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, parking garages and water storage tank are presented.

FRP DESIGN CODES AND GUIDELINES

A number of committees from professional organizations around the world have addressed the use of FRP bars in civil structures and published several standards and/or guidelines relevant to FRP as primary reinforcement for structural concrete. The recommendations ruling the design of FRP-reinforced concrete (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. The earliest design guideline for FRP-RC members was developed in Japan in 1997 (JSCE 1997). This design guideline was the basis for developing the early editions of FRP-RC design standards in North America.

In 2000, the Canadian Standard Association (CSA) has published its first edition of the Canadian Highway Bridge Design Code (CHBDC) [CAN/CSA S6-00] which included Section 16 for using FRP bars as main reinforcement in concrete bridges. Shortly after, the Canadian Network of Centres of Excellence on Intelligent Sensing for Innovative Structures published the design manual 3 (ISIS M-03) and for FRP-RC structures. In 2002, the CSA published the CAN/CSA S806-02 for the design and construction of building components with FRP bars. The enormous worldwide research efforts on different types of FRP materials during the last decade led to updating the building [CAN/CSA S806-12] and bridge [CAN/CSAS6-14] codes to encourage the construction industry to use FRP materials.

The American Concrete Institute (ACI) introduced its first guideline (ACI 440.1R) for the design and construction of concrete reinforced with FRP bars in 2001. Updated versions were introduced in 2003, 2006, and the latest edition was published in 2015 [ACI 440.1R-15]. In 2009, the American Association of State Highway and Transportation Officials (AASHTO) published its first edition (AASHTO LRFD Bridge Design Specifications) for the design of bridge components using GFRP reinforcing bars.

In Europe, the International Federation for Structural Concrete *(fib)* published its first report prepared by *Task Group 9.3*, for FRP reinforcement in RC structures in 2007. Italy has also developed the Italian guideline for the design of FRP-RC structures which was published in 2006 [CNR-DT 203-2006]. Continuous efforts are being conducted worldwide to adopt/develop design standards for FRP-RC.

With the increased use of FRP, there was a need to establish stringent guidelines and values for FRP manufacturers and quality control mechanisms for owners to ensure the quality of product supplied. The ACI developed a new standard entitled Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement [ACI 440.6M-08]. In 2010 the CSA presented the first Specification for Fibre-Reinforced Polymer (FRP) [CAN/CSA S807-10] which was developed on the basis of the Specifications for Product Certification of FRP's by ISIS Canada Corporation in 2006. The CAN/CSA S807-10 Specification covers the manufacturing process requirements for FRP bars and grids (using only aramid, carbon, or glass fibres) to be used in non-prestressed concrete members as internal reinforcement. It also classified the FRP on the basis of their fibres, strength, stiffness, and durability.

Nowadays, the most recent edition of the CHBDC [CAN/CSA S6-14] provides a wide acceptance for new bridge applications. In addition, the most recent building design standard [CAN/CSA S806-12] has been improved based on the latest research results and experience in the field. It provided new provisions on: punching-shear at slab-column connections, confinement of columns by FRP internal ties or hoops, design of FRP-RC 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 standard covers all the basic design requirements for FRP reinforced and retrofitted structures.

FRP REINFORCING BARS

Advantages

The technology of RC is facing a serious degradation problem 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 since they are lightweight (1/4th weight of steel), corrosion resistant, and offering excellent tensile strength and high mechanical performance. In addition, FRP bars are 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. 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.

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	0.0151 – 0.0211

RECENT FIELD APPLICATIONS

Highway Bridge Structures

Corrosion of steel reinforcing bars stands out as a significant factor limiting the life expectancy of reinforced concrete bridges. In North America, 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 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. Problems related to expansive corrosion could be resolved by protecting the steel bars from corrosion-causing agents or by using noncorrosive FRP bars.

Since the late 1990s, the Structures Division of the Ministry of Transportation (MT) at different provinces has been interested in building more durable bridges with an extended service life of 75–150 years. For example, the Ministry of Transportation of Quebec (MTQ), Canada has carried out, in collaboration with the University of Sherbrooke, (Sherbrooke, Quebec), several research projects utilizing the straight and bent GFRP bars in concrete deck slabs and bridge barriers (Benmokrane et al. 2006&2007; Ahmed et al. 2013a&b; Ahmed et al. 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 in hundreds of bridges across Canada and USA, see figure 1. These bridges were designed using the Canadian Highway Bridge Design Code or the AASHTO LRFD Bridge Design Guide Specifications for GFRP-RC Bridge Decks and Traffic Railings. Straight and bent GFRP bars were used mainly as internal reinforcement for the deck slab and/or for the concrete barriers and girders of these bridges. The bridges were of slab-on-girder type with main girders made of either steel or prestressed concrete. The main girders were simply supported over spans ranging from 20.0 to 90.0 m. The deck was 200 to 260 mm thick concrete slab continuous over spans of 2.30 to 4.0 m. Most of these bridges have been reinforced with the GFRP bars as a result of their relatively low cost compared to other types of FRPs (carbon and aramid).

(a) Gateway Blvd/23rd Ave –Alberta (2009) (b) 410 Overpass Bridge Quebec (2012)

Figure 1. Recent Application of GFRP in Concrete Bridges

Recently, the GFRP bars have been used as the main reinforcement in the deck slab of Nipigon River cable stayed (see figure 2) on Highway 11/17, ON, Canada. This bridge includes cable-supported spans of 112.8 m and 139 m. The 36.2 m wide deck consisted of concrete panels totally reinforced with GFRP bars and supported on transverse steel beams. The GFRP bars were used to overcome the steel expansive-corrosion issues and related deterioration problems and to design durable and maintenance-free 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 and Benmokrane 2012).

Figure 2. Nipigon Cable-Stayed Bridge, ON, Canada

Water Tanks

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 FRP 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 m^3, 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 (Mohamed and Benmokrane 2014). This included the use of high modulus GFRP bars (Grade III, CSA S807-10) as main reinforcement for the foundation, walls and top slab. Figure 3(a) and (b) show the FRP bars 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.

(a) FRP reinforcement of the wall (b) Overview of the tank

Figure 3. GFRP-Reinforced Concrete Tank, QC, Canada

GFRP Soft-Eyes in Tunnels

GFRP bars can be used in tunnel applications as soft-eyes because they have very high tensile strength which can reach far over 1200 N/mm^2. Besides the GFRP bars can be cut with working tools like saws, pilling/drilling equipment and Tunnel Boring Machines (TBM). This avoids damages to cutter heads and does not delay the work progress as piling or cutting through GFRP bars is unproblematic. The bars are split in small pieces which do not harm slurry pipes.

During tunnel construction, breaking through the steel reinforced walls of the excavation shaft with a TBM required extensive measurements and preparation work, (Schürch and Jost 2006). The anisotropy of GFRP bars is quite advantageous at excavation pits for the starting and finishing processes at automated excavation like TBM and Pipe jacking, see figure 4(a). Therefore, using GFRP bars in reinforced walls and piles of the excavation shaft 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, see figure 4(b), (c) and (d). The sections below and above the tunnel opining are reinforced with steel bars. Depending on the designer and contractor 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, see figure 4(b) and (d). 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). GFRP reinforcing cages of diameters raining from 600 to 1100 mm were used. Grade III (60 GPa, CSA S807-10) 32.0 m vertical bars were used with Grade II (50 GPa, CSA S807-10) size #5 (16.0 mm) continuous spirals with 150 mm pitch, see figure 4(b) and (c).

(a) TBM cutting through FRP-RC wall

(b) GFRP reinforcing cages for soft-eye

(c) Handling and lifting the GFRP soft-eye

(d) Soft-eye reinforcement for a diaphragm wall

Figure 4. GFRP Reinforcement for Soft-Eyes, ON, Canada

Parking Garages

The need for sustainable structures has motivated the Public Works and Government Services Canada (PWGSC) to use FRP bars as internal reinforcement in concrete infrastructure applications. One of the most important successful applications is using GFRP bars in reinforcing the parking garage. An agreement between PWGSC and the University of Sherbrooke was reached to reconstruct the interior structural slabs of the Laurier–Taché parking garage (Hull, Quebec) using GFRP bars (Benmokrane et al. 2004), see figure 5(a). The design was made according to CAN/CSA S806-02. This project allowed direct field assessment and long-term monitoring of FRP composite bars in a structure subjected to harsh environmental and loading conditions. In 2010, the new large parking garage (La Chancelière parking garage, area 3000 m^2) in Quebec City was designed and constructed using the GFRP bars as main reinforcement (Ahmed et al. 2016). This design was made according to the CAN/CSA-S413-07 for parking structures and CAN/CSA S806-02 for Design and Construction of Building Components with Fibre-Reinforced-Polymers. The two-way flat slabs of La Chancelière had maximum span of about 9.0 m. The thickness of the slabs was 250 mm which increased to 355 mm over the columns through the drop panels, see figure 5(b). The increased thickness over the columns was devoted to satisfy the punching stresses around the columns' area. The punching strength of the two-way slabs were verified using the new punching equations of the CAN/CSA S806-12 which has been calibrated using the experimental testing of full-scale testing conducted at the University of Sherbrooke (Dulue et al. 2013; Hassan et al. 2013&2015).

(a) Laurier-Taché parking garage

(b) La Chancelière parking garage

Figure 5. GFRP Bars Applications in Parking Garages, QC, Canada

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. GFRP bars are 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 and Davidson 2006). These observations, coupled with the knowledge that up to 65 tons of salt per year can be spread on a 1 km (0.6 mile) long stretch of a two-lane pavement in Montreal (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 GFRP bars for CRCP since 2006. In September 2006, a 150 m long section of eastbound Highway 40 (Montreal) was selected as a demonstration project (Benmokrane et al. 2008). 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. In February 2008, the measured results showed that the average crack spacing varied between 1.5 and 4 m in most CRCP-GFRP slabs. In addition, the average crack width varied between 0.7 and 0.9 mm, which is less than the AASHTO design limit of 1.0 mm (Benmokrane et al. 2008).

In September 2013, it was decided to use GFRP bars in one of Quebec's CRCP highways (300 m long). A stretch of test pavement has since been constructed on westbound Highway 40 in Montreal. The project is located on eastbound Highway 40 in Montreal, QC, and presents a collaboration between the MTQ and the University of Sherbrooke. A variety of sensors were installed in this project to monitor the early-age behavior and the effects of repeated traffic loads and environmental conditions on the performance of CRCP slab. The test slab was 315 mm (12.4 in.) thick with a GFRP reinforcement ratio of 1.2%. The reinforcement ratio for steel bars in the CRCP steel-reinforced slab is 0.1% for transverse rebar and 0.74% for longitudinal bar, see figure 6. According to observations at 16 months, the crack spacing and crack width in the steel-reinforced CRCP test section were larger than those of the GFRP-reinforced CRCP section. The field performance of the GFRP CRCP appeared satisfactory, particularly because the crack widths satisfied the AASHTO limiting criterion for crack width as ≤ 1 mm (0.04 in.), which is essential in maintaining pavement integrity by securing adequate aggregate interlock at the crack. Data from this experimental phase will allow for finite-element modeling of the CRCP-GRFP slab.

Figure 6. GFRP Bar Placement in Center Lane in Highway 40, Montreal, QC, Canada

CONCLUSION

The observations and the outcomes from the different field applications reported in this paper can be summarized 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, parking garage structures and continuously reinforced-concrete-pavement provide excellent applications for the use of FRP in new construction.

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