Recent Canadian Developments Related to FRP Reinforcement for Sustainable and Resilient Concrete Structures, Design Codes, and Field Applications in Infrastructures and Buildings

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Abstract. Extensive research and field practices have established the design principle of using fiber-reinforced polymer (FRP) bars to reinforce concrete structures. Material specifications and design aspects are now regulated through provisions governing certification testing, quality control/assessment, and FRP design. The Canadian Standards Association (CSA) updated two provisions related to FRP materials and design. The 2019 edition of CSA S807 includes modifications to quality and qualification requirements, material properties, testing procedures, and material mechanical and durability limitations. Section 16 of CSA S6 (2019) was also updated to provide more rational design algorithms for fiber-reinforced structures and highway bridges, allowing practitioners to fully utilize the efficiency and economic appeal of FRP bars. Additionally, the recent editions of CSA S900.2 (2021) on the structural design of wastewater treatment plants and CSA S413 (2021) for parking garages include provisions on the use of FRP bars as high-durable reinforcement. This paper provides an overview of the recent changes in Canadian codes and standards and explains the reasoning behind them. It also highlights examples of recent field applications of FRP bars in various types of concrete civil-engineering infrastructure.

Keywords: Fiber-Reinforced Polymer (FRP) Reinforcement · Reinforced Concrete · Standards · Field Applications

1 Introduction

Corrosion of steel reinforcement due to electrochemical processes is a major cause of infrastructure deterioration worldwide, posing a significant challenge for the construction industry. However, corrosion-resistant materials such as high-performance fiber-reinforced polymer (FRP) composites offer an effective solution to overcome this issue. Over the past few decades, successful applications of FRP reinforcement in concrete structures around the world have demonstrated its practicality and effectiveness. As a result, the use of FRP composites in place of steel reinforcement has been increasing to

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overcome the common issues caused by steel corrosion, particularly in regions where large amounts of de-icing salts are used during winter and elements exposed to aggressive environments such as seawater salts.

Compared to conventional steel, FRP materials offer several advantages, including greater resistance to corrosion even in harsh chemical environments, one-quarter to one-fifth the density of steel, neutrality to electrical and magnetic disturbances, and higher tensile strength than steel. However, designers shall account for the lower modulus of elasticity of FRP bars compared to steel, which necessitated regulating the design and specifications of FRP bars through the development of the first generation of design provisions.

Over the years, numerous studies have been conducted to update the first-generation design guides for FRP-reinforced concrete structures. These updates have allowed for a relaxation of originally over-conservative assumptions, making it possible to make more efficient use of FRP bars. The design provisions successfully addressed the behavior of FRP RC structures and their differences from conventional steel RC members. However, ongoing research is necessary to further develop codes and standards and make design provisions more rational and sustainable, thereby enabling practitioners to take full advantage of the efficiency and economic appeal of FRP bars.

This paper aims to demonstrate the growing acceptance of FRP bars worldwide. The most significant successes of FRP reinforcement have been in reinforced-concrete highway bridges, parking garages, tunneling, and marine structures, where corrosion resistance and installation flexibility are significant benefits. The following sections of this paper describe the development of Canadian codes and guidelines related to FRP reinforcement, as well as recent examples of its use in bridges, tunnels, parking garages, buildings, and water storage tanks.

2 Latest Updates of Canadian Standards

The Canadian Standard Association (CSA) group released two new code editions related to FRP reinforcement: CSA S807 [1] and CSA S6 [2]. The main objective of CSA S807 [1] is to establish stringent guidelines and values for FRP bar manufacturers and quality-control mechanisms for owners, ensuring a high level of confidence in the product supplied. On the other hand, the new edition of CSA S6 [2] aims to make the provisions for the use of FRP reinforcement more rational, offsetting some over conservativeness and making the design approach consistent with Section 8 of the same code for conventional construction materials.

Two other CSA Standards were also recently updated and published and incorporated requirements related to the design and construction using FRP reinforcement. The CSA S900.2 [3] provides requirements and guidance on the structural design of new wastewater treatment plants, including buildings and liquid-containing tanks, from the point effluent enters the plant to the point of its discharge. On the other hand, CSA S413 [4] specifies requirements for the durability aspects of the design and construction of new parking structures and parts of buildings subject to vehicular traffic. The following sections detail the significant developments introduced in CSA S807 [1], Section 16 of CSA S6 [2], and the FRP sections in CSA S900.2 [3] and CSA S413 [4].

2.1 Canadian Standard on Material Specifications

The Canadian Standard CSA S807-19 [1] is a comprehensive document that outlines the manufacturing process and performance requirements for FRP bars used in non-prestressed internal reinforcement of concrete components of structures such as bridges, buildings, and marine structures. The standard specifies the allowable constituent materials, volume limits, and minimum performance requirements for FRP bars, including testing methods for product qualification and quality control/assurance, for FRP with diameters from 6 mm to 36 mm. Several FRP manufacturers/suppliers worldwide have qualified their products using CSA S807 [1] and obtained approvals from end users and government authorities (Fig. 1).

The updated version of the standard [1] is notable for being the first standard to include specifications for basalt fiber-reinforced polymer (BFRP) as a material for reinforced concrete structures. The inclusion of BFRP in the updated CSA S807 [1] standard is a significant step following the published studies on the behavior of BFRP-reinforced concrete structures [5]. Furthermore, the new material specifications restrict the use of glass fibers to corrosion-resistant E-CR glass fibers that meet ASTM D578 [6] requirements. The standard also introduces requirements for sand used as sand-coating for FRP bars and precludes the use of sand particles exhibiting any sign of expansive reaction [7]. Additionally, quality-control tests must now be performed on each production lot of FRP reinforcement, with specific requirements for lot sizes and testing parameters.

The standard divides the performance of FRP bars into three different grades according to their mechanical and durability characteristics, with new limits of mechanical properties introduced for each grade. The standard also specifies lower and upper boundaries for the cross-sectional area of FRP bars. The updated version of CSA S807 [1] introduces the apparent horizontal shear strength according to the short-beam shear test as a tool to detect the efficiency of the fiber/resin interface property of FRP bars. More restrictive requirements for the tensile and interlaminar shear strength retentions in high pH solutions at an elevated temperature of 60 °C were also stipulated. Additional requirements for the durability of FRP bars with end heads (Fig. 1) have been presented. The durability of headed GFRP bars is assessed by conditioning in alkaline solutions and exposure to sustained load for a period of 120 days at 60 °C, while the strength retention at the headed end shall be more than 80%. Furthermore, the standard adopted a new testing procedure for the strength of FRP bent bars at the bent portion [8].

Fig. 1. FRP materials accepted by CSA S807 [1] (Courtesy of PohlCon GmbH, Germany).

2.2 Canadian Standard on Highway Bridge Design

The Canadian Standard CSA S6 [2] provides guidelines for the design, evaluation, and rehabilitation of highway bridges in Canada. The standard's Section 16 outlines the design of FRP-reinforced highway bridges, and it has been updated to reflect the state-of-the-art FRP design. The modifications include additional clauses for detailing bundled FRP bars, bent bars, and headed bars, changes to shear and torsion design, and recommendations for the repair of damaged bridge components reinforced with FRP bars. The code also adopted requirements for the design and detailing of Discontinuity or Disturbed Regions (D-regions) in deep beams, corbels, and short walls using the strut-and-tie method. Requirements for the tensile strength of ties, compressive strength of struts and nodes, and the required anchorage length of longitudinal reinforcement are given.

The standard now endorses the use of FRP reinforcement in compression members, allowing compressive strength up to 0.002, although this is considered conservative. The compressive strain limit of 0.002 for FRP bars reflects the nominal capacity of tested FRP-reinforced columns, as demonstrated by the results of Afifi et al. [9] and Mohamed et al. [10], where FRP bars developed up to 0.4% compressive strain before crushing of the concrete. Another significant change in the standard is the resistance factor for GFRP reinforcement, which has been increased to 0.65 in the current standard version from 0.55 in the previous version. This increase follows the recommendations by recent studies on the durability of GFRP bars, suggesting that the environmental reduction factor of GFRP can be relaxed to 0.85 [11, 12]. Furthermore, the creep rupture strength limit for GFRP reinforcement remains at 0.25 of the ultimate tensile strength, but it is expected to be relaxed to 0.3 in the next edition of the standard, which has been the findings of recently published studies [13].

The next edition is also expected to include BFRP reinforcement, following the inclusion of the BFRP material specification in the CSA S807 [1]. The standard's next edition is also expected to include recommendations for the splice length of FRP under compression and the slenderness ratio of FRP-reinforced compression members. Moreover, the next edition will present substantial modifications for FRP transverse reinforcement in compression members, including specifications for FRP transverse reinforcement located in plastic hinge regions and guidelines for seismic considerations [14, 15].

2.3 Canadian Standard on Structural Design of Wastewater Treatment Plants

Wastewater treatment plants are critical infrastructure facilities that play a vital role in ensuring public health and environmental safety. However, these facilities are often subject to corrosion-related problems due to harsh operating conditions, including exposure to chemicals and high humidity levels. This can jeopardize the structural integrity of the facilities and compromise public health and environmental safety. To address these issues, the CSA S900.2 [3] Standard has been developed to provide guidance on the design of structural elements within wastewater treatment plants. To mitigate the risk of public health and environmental safety, the use of GFRP reinforcement has been adopted by the CSA S900.2 [3] standard as a cost-effective solution when corrosion is of concern [16].

The standard recommends more stringent requirements for the crack width to avoid leakage from wastewater treatment liquid containers. This emphasizes the importance of ensuring the integrity of the wastewater treatment plant's structure to minimize the risk of contamination and ensure public safety. By stressing the need for high-quality materials and construction techniques and providing recommendations for cost-effective solutions such as GFRP reinforcement, the standard helps to ensure the long-term performance and safety of these critical infrastructure facilities.

2.4 Canadian Standard on Parking Garages

The CSA S413 [4] Standard provides comprehensive durability requirements for the design and construction of new parking structures subject to vehicular traffic, with specific recommendations on materials and methods to mitigate or eliminate corrosion of reinforcement. The standard addresses both ultimate and serviceability limit states to protect against the deterioration of concrete caused by de-icing chemicals alone, as well as de-icing chemicals in combination with the effects of freeze-thaw cycling.

The most recent edition of the standard has been updated to include the use of GFRP bars for reinforcing parking structures due to their superior resistance to a broad range of chemicals [17]. When using GFRP reinforcement, no additional protection methods, such as cathodic protection, are required. The standard also specifies that less restrictive concrete covers can be used with GFRP reinforcing bars while maintaining protection against water leakage through the roof, suspended floors, and below-grade foundation walls.

According to CSA S413 [4], the design of GFRP-reinforced elements should be in accordance with the building code for FRP-reinforced structures, CSA S806 [18]. Overall, the standard provides important guidance for ensuring the long-term durability of parking structures and other buildings subject to vehicular traffic, and its inclusion of GFRP reinforcement offers an innovative and potentially cost-effective solution for meeting these requirements.

3 Recent Field Applications

The Canadian Standards on the design and construction of FRP-reinforced structures have been followed in the design and construction of hundreds of structures in Canada, Europe, and worldwide, such as highway bridge structures, parking garages, precast piles, water tanks, concrete pavement continuously reinforced with GFRP bars, concrete sleepers, underground utilities (Guerin et al. 2016). Below is a brief description of some projects.

3.1 Highway Bridges

The incorporation of FRP bars as reinforcement for concrete bridges has shown potential for extending the service life of such structures, along with providing economic and environmental benefits. Since the late 1990s, FRP bars have been used successfully in hundreds of bridge structures across Canada and the world. The use of FRP bars to reinforce deck slabs, barriers, and girders has been effective in increasing the service life of the bridge. However, the more recent use of FRP bars to reinforce the entire bridge, including the deck and approach slabs, abutments, columns and piers, and piles and pile caps, has become prevalent.

One such recent example of a completely reinforced GFRP bridge is the Clyde River Bridge, located on Prince Edward Island, Canada. This bridge is a two-lane, two-span steel box-girder bridge that relies on GFRP-reinforced abutments and a middle pier supported by GFRP-reinforced pile caps and steel-pipe piles. It is the first bridge in the world to be completely reinforced with GFRP bars. Another example is the West Street Underpass Bridge Replacement project, which was designed by the Ministry of Transportation of Ontario (MTO) in accordance with Section 16 of the newly published CSA S6 [2] standards. This $20 million project involves the use of GFRP bars to reinforce various components, including footings, columns, abutments, wingwalls, pier caps, deck slabs, parapets, sidewalks, and their connections. MTO is also working on the design of other bridges entirely reinforced with GFRP bars (Fig. 2).

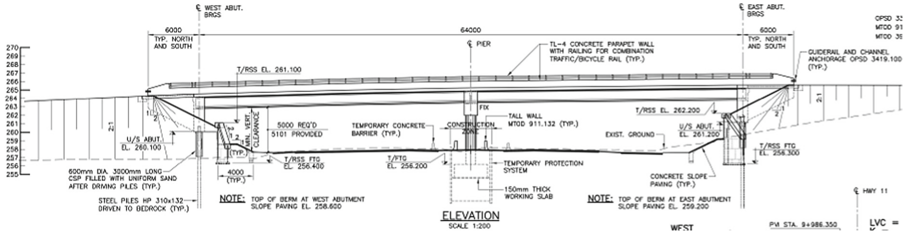

Fig. 2. GFRP-Reinforced bridge replacement by the Ministry of Transportation of Ontario.

3.2 Parking and Building Structures

The demand for sustainable structures has prompted owners to explore the use of FRP reinforcement as a durable and non-corrosive material. One successful application has been the use of GFRP rebar in parking and building structures exposed to aggressive environments or magnetic fields interfering with steel reinforcement. For instance, the Nuclear Physics Institute in Prague, Czech Republic, GFRP bars were used to reinforce the Tokamak reactor slab and its supporting columns (Fig. 3a). Double-headed shear reinforcement GFRP bars were employed to boost the slab's punching shear capacity at the column locations, following the findings by El-Gendy and El-Salakawy [19]. The CSA S806 [18] recommendation was used to design the slab and column reinforcement. Similarly, in the nuclear medicine facility at Zurich University (Fig. 3b), GFRP reinforcement was used to strengthen the building slab according to EC2 recommendations [20].

In addition, GFRP was used in transformer foundations in a German power plant due to its non-conductivity characteristics (Fig. 4). The Zurich airport taxiway also utilized GFRP as the material of choice because of its conductivity neutrality and resistance to corrosion from de-icing salts and chemicals (Fig. 5). These examples demonstrate the potential of FRP reinforcement for enhancing the durability and sustainability of structures.

Fig. 3. a) GFRP shear reinforcement of Tokamak reactor slab, and b) GFRP bars in the slab of Zürich University Nuclear Medicine (Photos by Christoph Spitz, PohlCon GmbH, Germany).

Fig. 4. Transformer foundation of electrical power plant in Germany (Photos by Christoph Spitz, PohlCon GmbH, Germany).

Fig. 5. GFRP in taxiways of Zürich airport (Photo by Christoph Spitz, PohlCon GmbH, Germany)

3.3 Secant Piles

Corrosion is a perpetual worry in the design and maintenance of infrastructure, particularly for elements that are exposed to harsh and coastal environments. FRP reinforcement has been used in many permanent secant piles to reduce life-cycle costs through reduced maintenance repairs and increased service life. One of the major projects was the secant-pile seawall/bulkhead, Flagler/Beverly Beach in Florida, USA [21]. The wall comprised 1847 GFRP-reinforced secant piles and a continuous cap. The secant pile shafts are (910 mm) in diameter and 11 m in length, reinforced with 25 No. 8 (25.4 mm) GFRP bars. Additionally, the secant piles of the Port Lands Flood Protection, Toronto, Canada, is a great example of large-scale projects. The 1200 mm diameter and 20 m deep shafts were designed based on the CSA S6 [2] recommendations. Each shaft was reinforced with a total of 38 bars with a diameter of 38 mm. The project was constructed in the Summer of 2021.

3.4 Soft-Eyes

Breaking through the steel-reinforced walls of the excavation shaft with Tunnel boring machines (TBMs) necessitates extensive measurements and preparation. To address these challenges, FRP has been extensively used to reinforce the excavation shaft walls and piles, which saves time and costs and offers corrosion resistance. Soft eyes made of bore piles or diaphragm walls reinforced with GFRP bars and stirrups are commonly used in the starting and finishing processes involved in automated TBM excavation and pipe jacking. The corresponding reinforcement cages can be built out of FRP bars on-site using similar work procedures as steel cages. The use of FRP bars in tunnel projects has been successfully demonstrated in various projects in Europe, including the Grand Paris Express Tunnel (Fig. 6), and Gotthard Base Tunnel railway through the Alps in Switzerland (Fig. 7). The FRP bars used in these projects have demonstrated high performance and effectiveness in tunnel project construction under actual service conditions.

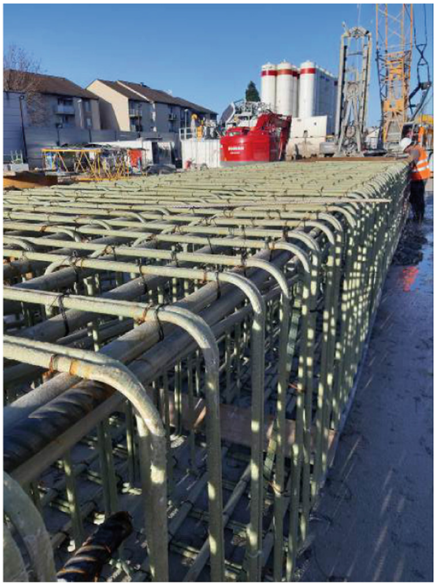

Fig. 6. GFRP in Grand Paris Express Tunnel (Photo by Christoph Spitz, PohlCon GmbH, Germany)

Fig. 7. GFRP cages in Gotthard Base Tunnel, Switzerland (Photos by Christoph Spitz, PohlCon GmbH, Germany).

4 Conclusions

This paper discusses the benefits of using FRP reinforcement in civil infrastructure, with field applications demonstrating its success. The paper also highlights the importance of regulations and provisions for testing, evaluation, and design aspects to guide FRP manufacturers and end-users.

The study further examines updated provisions issued by the Canadian Standards Association (CSA) [1–4] regarding FRP material specifications and design requirements. Various applications of FRP reinforcement in new construction, such as concrete bridge components, water tanks, diaphragm walls, and parking-garage structures, have demonstrated competitive performance compared to structures reinforced with steel bars. The available design provisions, recommendations, and limitations in international FRP codes and standards are adequate to meet serviceability and strength criteria in designing different concrete structures, offering the potential for major applications of FRP reinforcing bars globally. Moreover, FRP-reinforced concrete structures would have service lives of 100 years or more, compared to similar structures reinforced with steel, which require maintenance after 30 years.

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