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Field Application of FRP Bars in Tunnels

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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 such as bridges, parking garages, and marine structures in which the corrosion of steel reinforcement has typically led to significant deterioration and rehabilitation needs. On the other hand, in recent years however the use of FRP soft-eyes in construction of tunnels is becoming more and more popular. A unique use of FRP bars takes advantage of their “anisotropic” property, meaning they are strong along the main axis, but can be machined, abraded away or “consumed” by excavated Tunnel Boring Machines (TBM). This paper presents a summary of three field applications of FRP soft eyes in tunnel construction in Canada. The details of FRP reinforcements, material characteristics, projects location, codes limitation, design consideration and construction are presented.

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. Canada Construction Association (CCA) has estimated that the global infrastructure loss would be in the vicinity of $900 billion. 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). 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; El Salakawy et al. 2003).

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 investigating, public agencies and regulatory authorities as the Public Works and Government Services Canada (PWGSC) and Ministry of Transportation at different provinces across Canada has now included FRP bars as a premium corrosion resistant reinforcing material in its corrosion protection policy.

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, (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.

The following sections present a general overview of using FRP bars in tunnels, the details of FRP reinforcements, material characteristics, projects location, codes limitation, design consideration and construction material characteristics of three field applications of FRP soft-eyes in tunnel structures in Canada.

2 TUNNEL BORING MACHINES

The tunnel boring machine (TBM) is a machine which has been developed in recent years and has revolutionised the tunnelling industry both making tunnelling a safer, more economical solution for creating underground space and opening the possibility of creating tunnels where it was not feasible before. A TBM also known as a "mole", is a machine used to excavate tunnels with a circular cross section through a variety of soil and rock strata.

They can bore through anything from hard rock to sand. Tunnel diameters can range from a metre (done with micro-TBMs) to 19.25 m to date. Tunnels of less than a metre or so in diameter are typically done using trenchless construction methods or horizontal directional drilling rather than TBMs.

Tunnel boring machines are used as an alternative to drilling and blasting (D&B) methods in rock and conventional "hand mining" in soil. TBMs have the advantages of limiting the disturbance to the surrounding ground and producing a smooth tunnel wall. This significantly reduces the cost of lining the tunnel, and makes them suitable to use in heavily urbanized areas. The major disadvantage is the upfront cost. TBMs are expensive to construct, and can be difficult to transport. However, as modern tunnels become longer, the cost of tunnel boring machines versus drill and blast is actually less, this is because tunneling with TBMs is much more efficient and results in a shorter project.

A few years ago starting and receiving a TBM in an excavation shaft required extensive measures for breaking through the walls of the shaft, which is secured out of steel reinforced concrete. This preparation work needed time and has been expensive. TBMs cannot cut through steel-reinforced concrete drilled shaft walls as the steel bars get caught in the shovels of their shield. In addition, the steel bars cannot be cut into pieces small enough to allow their transport by the TBM's conveyor belt system. The anisotropy of the FRP bars is quite advantageous at excavation pits for the starting and finishing processes of tunnels. GFRP material 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 fibre bars are split in small pieces which do not harm slurry pipes, see Figure 1.

Figure 1. TBM cutting through FRP-reinforced concrete drilled shaft wall.

3 DEVELOPMENTS OF CODES AND GUIDELINES

In North American, several codes and design guidelines for concrete structures reinforced with FRP bars have been published from 2000 to 2010. 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 reinforcements. The American Concrete Institute (ACI) introduced the first and second guideline (ACI 440.1R) for the design and construction of concrete reinforced with FRP bars in 2001 and 2003, respectively. 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 [ISIS-M03-2007; CAN/CSAS6-06; CAN/CSAS6-06 edition 2010; ACI 440.1R-03; ACI 440.1R-06]. Currently out for comment, a revised ACI 440.1R-06 and CAN/CSA-S806-02 is forthcoming later in 2012.

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 FRP specification (CSA S-807-10), which is now available from the CSA website since 2010.

4 GFRP SOFT-EYE

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.

The removal of the retaining wall or piles prior to the launch is clearly a high risk activity since after that there is no more safety device left until the shield has passed through the sealing block, the first segment rings have been installed and the tail skin grouting has been performed. Very often launching shafts are built to a great depth (20m to 40m below the ground) and have to resist ground and water pressure. For this reason the piles or walls are built with a consistent thickness (1 to 2 m) and are reinforced with enormous steel reinforcing bars. Before the TBM starts boring the tunnel, breaking of the wall is done manually as well as the cutting of the steel reinforcing bars (IMIA Conference Istanbul, WGP 60-09).

This is the reason why nowadays a "smart solution" offered by GFRP the so called "soft eye" method – is increasingly more adopted. The technique consists of substituting the internal steel reinforcement bars of the

concrete wall with composite materials bars having a high tensile strength but low shear strength, which allow the TBM to bore through the wall section easily and without running any risk for the cutting tools and minimizing the risk of water ingresses and ground subsidence.

Building the corresponding reinforcement cages out of GFRP bars on site requires the same working procedures as for an equal steel cage, see Figures 2 and 3. The necessary bars are tailor made and delivered to site where the assembly takes place. The bars are fixed together with binding wire, cable binders or similar products. U-bolts are used for clamping bars together when high loads have to be transferred over a connection. This is the case for example in the connection between vertical GFRP bars and the corresponding steel bars which have to carry the dead load of the reinforcement cage during the lifting process and lowering of the cage into the trench. Welding as is commonly done with steel reinforcement in such situations is not possible with GFRP bars (Schürch and Jost 2006).

Figure 2. Lifting up the Soft-Eye

Figure 3. Soft-Eye reinforcement for a diaphragm wall.

4.1 Mechanical Properties of FRP Bars

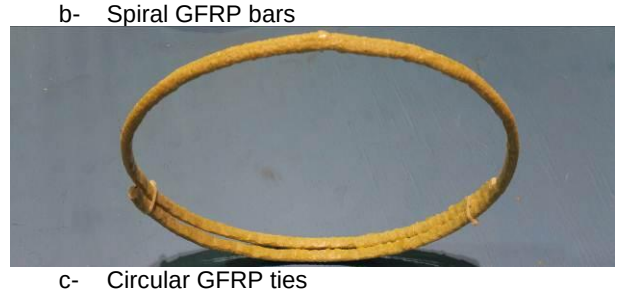
Sand-coated GFRP straight bars and spiral stirrups were used as reinforcement for the Soft-Eyes investigated in this study. The FRP bars are made of continuous fibers (glass) impregnated in a vinyl ester resin using the pultrusion process, manufactured by a Canadian company [Pultrall Inc., Thetford Mines, Quebec]. Table 2 presents the mechanical properties of the FRP bars as specified by CSA S807-10 for the three different Grades. These bars were made of high strength E-glass fibers with a fiber content of range 65% to 85% in a vinyl ester resin. The minimum guaranteed tensile strength and the tensile modulus of elasticity of the GFRP bars used in reinforcing the soft-eyes in the three different projects were as presented in Table 2, Grade II for spiral stirrups and Grade III for straight bars.

Table 1. Typical Mechanical Properties of V-ROD GFRP Bars Manufactured by Pultrall Inc.

Grade	Trade Name	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Ultimate Tensile Strain
I	V- Rod LM	588 - 804	40 - 47	0.0134 – 0.0189
II	V- Rod SM	703 - 938	50 - 59	0.0133 – 0.0179
III	V- Rod HM	1000 - 1372	60 - 69	0.0151 – 0.0211

a- GFRP bars

b- Spiral GFRP bars



c- Circular GFRP ties

Figure 4. Different types of GFRP reinforcements.

4.2 ADVANTAGES

The technology of reinforced concrete is facing a serious degradation problem in structures due to the corrosion of steel rebar. 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.

Fiber-reinforced polymer (FRP) bar has 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 work involved in preparing the shaft constructions for the TBM launch/receive for example. Also, the weight of a GFRP 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.

On the technical level, GFRP products have important advantages. GFRP reinforcement bars used in the soft-eyes of this study 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 fibre bars are split in small pieces which do not harm slurry pipes.

5 DESIGN CONSIDERATIONS

There are a number of authoritative consensus design guidelines for the designer to follow. Generally the design methodology for FRP reinforced concrete members follows that of steel reinforcing but taking into account the linear elastic or non-ductile nature of the material with different safety factors. Care is taken to avoid the possibility of a balance failure mode where concrete crushing and rupture of the bar could occur simultaneously. The designer must choose between compression failure of concrete, which is the preferred mode as recommended by the S806-12, and rupture of the FRP bar with a higher factor of safety, (ACI440-1R-08 and S6-06 Edition 2010). The soft-eyes of this study were designed by the consult firm engineers considering the flexural and shear design provisions provided in the Canadian Standards Association (CSA) 2002, Design and Construction of Building Structures with Fibre Reinforced Polymers (CAN/CSA S806–02). Also, the design was reviewed by the Department of Civil Engineering, University of Sherbrooke, (led by the Research Chair Professor Brahim Benmokrane).

The following two sections provide a summary about the flexural and shear design provisions used in the design of soft-eyes:

5.1 Flexural Design

Recently, the application of the circular GFRP-reinforced piles (soft-eyes) is new and rapidly increasing in the field of tunnel structures. All the codes and design guidelines provide flexural design provisions and equations for the reinforced concrete beams based on they have rectangular cross section. This is resulted from the common practical use of the rectangular reinforced concrete beams in civil engineering structures. Circular axi-symmetric flexural members are desirable in certain applications, including concrete piles and pier columns. In fact, the analysis of a circular cross section is more complex than that of a rectangular one. The stresses, which are variable over the section depth, are also distributed along an area of variable width. In addition, the bars are usually disturbed throughout the depth, such that the cross-sectional area of reinforcement at any given depth is more difficult to calculate than in conventional RC sections.

Simplified analytical method is developed to predict the resisting moments corresponding to the compression failure mode of the FRP soft-eye. The analysis was conducted according to the equations derived from linear elastic analysis, and assuming Bernoulli's theory (plane section remains plane). The flexural analysis procedure was straightforward. In tension the concrete is assumed not to contribute to the internal forces after cracking.

- Maximum strain at the concrete compression fibre is 3500×10^{6}.
- Tensile strength of concrete is ignored for cracked sections.
- The strain in concrete and FRP at any level is proportional to the distance from the neutral axis.
- The stress-strain relationship for FRP is linear up to failure.
- Perfect bond exists between the concrete and the FRP reinforcement.
- Strain compatibility method shall be used to calculate the factored resistance of a member
- Flexural members shall be designed such that failure at ultimate is initiated by the failure of concrete at the extreme compression fiber. This condition is satisfied by the c/d requirement shown below:

$$\frac{c}{d} \geq \frac{7}{7 + 2000\,\varepsilon_{Fu}} \qquad [1]$$

Where,
c *: neutral axis depth*
d *: depth of the pile (assumed 0.72 diameter)*
ε_{Fu} : *ultimate tensile strain of the FRP bars as provided by the manufacture*

- The maximum strain in GFRP tension reinforcement under sustained service loads shall not exceed 0.002.

- The maximum stress in FRP bars or grids under loads at serviceability limit state shall not be more than: 0.25 of the characteristic tensile strength.

- When the maximum strain in FRP tension reinforcement under full service loads exceeds 0.0015 (S806) the following equation should be considered:

$$z = k_b \frac{E_s}{E_F} f_f \sqrt[3]{d_c A} \qquad [2]$$

Where:

Z : quantity limiting distribution of flexural FRP reinforcement bars does not exceed 45 000 N/mm for interior exposure and 38 000 N/mm for exterior exposure,

k_b : bond dependent coefficient (0.8 for V-ROD).

A : effective tension area of concrete surrounding the flexural tension reinforcement,

f_f : stress in the tension FRP reinforcement at location of the crack, MPa,,

d_c : concrete cover measured from the centroid of tension reinforcement to the extreme tension surface, mm

E_F : Modulus of Elasticity of FRP bars.

5.2 Shear Design

The shear strength of the soft-eyes was verified using the shear design provisions of the S806 Standard (CAN/CSA S806-02 2002) of the following equations:

$$V_n = V_{cf} + V_{sf} \qquad [3]$$

where

V_n = nominal shear strength

V_{cf} = concrete contribution to shear strength

V_{sf} = shear reinforcement contribution to shear strength

The concrete contribution to shear strength V_{cf} is calculated using the following equations:

$$V_{cf} = 0.035\phi_c \left(f_c' \rho_f E_f \frac{V_f}{M_f} d \right)^{\frac{1}{3}} b_w d$$

$$where: \qquad [4]$$

$$0.1\sqrt{f_c'}\, b_w d < V_{cf} > 0.2\sqrt{f_c'}\, b_w d$$

$$Min\ V_c = 0.1\sqrt{f_c'}\, b_w d$$

$$Max\ V_c = 0.2\sqrt{f_c'}\, b_w d$$

For sections with an effective depth greater than 300 mm V_{cf} is taken as

$$V_{cf} = \left[\frac{130}{1000 + d} \right] \lambda \phi_c \sqrt{f_c'}\, b_w d \geq 0.08 \lambda \phi_c \sqrt{f_c'}\, b_w d \qquad [5]$$

$$V_{sf} = \frac{0.4\phi_f A_{fV} f_{fuv} d}{s} \leq 0.08 \lambda \phi_c \sqrt{f_c'}\, b_w d \sqrt{\frac{E_{fv}}{E_s}} \qquad [6]$$

6 TUNNEL FIELD PROJECTS USING FRP BARS

The following sections describe three selected field applications of the FRP bars in tunnel projects. The unique features of each project are highlighted.

6.1 TTC Subway North Tunnels - Toronto, ON (South Tunnels - Keele Station, Hwy 407 Station)

The second major contract for the Toronto-York Spadina Subway Extension (TYSSE) project was awarded in January 2011 to Obrascon Huarte Lain (OHL), in joint venture with Fomento de Construcciones y Contratas (FCC) for the Highway 407 Subway Station & Northern Tunnels contract. Construction is underway for this contract which includes construction of the Highway 407 Station and tunnelling of 6.6 kilometres of tunnel by 2 of the 4 Tunnel Boring Machines (TBMs). The tunnelling and station construction activities will run in parallel. A construction area has been established on the west side of Jane Street south of Highway 407 for station construction. The advanced launch shaft was located on the northwest section of York University's Keele campus at Northwest Gate and Steeles Avenue West.

Project highlights:

- V-ROD GFRP bars were used to reinforce up to 19.0 m long GFRP cages (diameters of 600 mm – 920 mm).
- Highest grade 60 GPa 32M vertical bars were used with # 5 (16M) 50 GPa continuous spirals with 150 mm pitch and inside 16M circular ties at 600 mm, see Figures 5 to 7.
- V-ROD GFRP reinforcement was used in this specific tunneling application where TBM's can bore through "Soft-eye" areas of caisson reinforcement cages
- Trancels-Pultrall supplied V-ROD GFRP in caisson cages in a "soft-eye" tunneling application in the North Tunnels portion of the TTC $2.6 billion subway expansion project.
- Owner: TTC (Toronto Transit Commission) subway expansion
- Contractor: OHL-FCC-DIBCO/Gilbert Steel
- Engineers: Eptisa Engineering/Tara Engineering

Figure 5. Overview of the GFRP Soft-Eyes (Side view)

Figure 6. Overview of the GFRP Soft-Eyes showing the circular ties

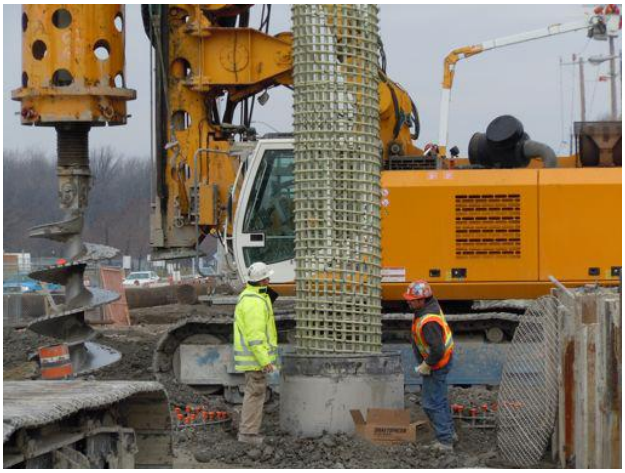


Figure 7. Handling and lifting the GFRP Soft-Eyes

6.2 Eglinton Crosstown LRT - Toronto, ON

The Crosstown is one of the largest and most ambitious infrastructure projects in North America. It will support future growth across Canada's biggest and fastest growing city. The Eglinton Crosstown LRT, or the Crosstown, is a combined underground/aboveground light rail line under construction in Toronto, Ontario, Canada. Initially known as "Eglinton Crosstown LRT" as part of the Transit City plan, the line was renamed following its temporary proposal to be built as a fully underground premetro line with the inclusion of the Scarborough RT line, to form the "Eglinton–Scarborough Crosstown line" collectively. After public debate about whether to keep the line entirely underground or to construct it partially underground, Toronto City Council and Metrolinx decided that the line will be built according to the way it was conceived in the Transit City plan in 2007. The line will be owned by Metrolinx and operated by the Toronto Transit Commission (TTC). Construction began in 2011 and is expected to be completed in 2020.

Project highlights:

- V-ROD GFRP bars were used to reinforce 11.8 m long GFRP cages (diameter of cages was 1100 mm)
- Highest grade 60 GPa 25M vertical bars and 15M braces were used along with #4 (13M) 50 GPa circular ties, see construction details Figures 8 to 10.
- V-ROD GFRP reinforcement was used in this specific tunneling application where TBM's can bore through "Soft-eye" areas of caisson reinforcement cages

- Trancels-Pultrall supplied V-ROD GFRP in caisson cages in a "softeye" tunneling application at the first launch site for the TBM's in the $8.2 billion Eglinton Crosstown Light Rail Transit project
- Owner: Metrolinx/GO Transit
- Contractor: Kenaidan Contracting Ltd./Harris Rebar/Bermingham
- Engineers: Isherwood Associates

Figure 8. Overview of the GFRP Soft-Eyes

Figure 9. Overview of the GFRP Soft-Eyes connection with steel cages

Figure 10. Driving the GFRP Soft-Eyes

6.3 The Coxwell Sewer Shaft

In the late 1950s, to facilitate the expansion of the city of Toronto a 2.6 m ID trunk sewer was installed connecting northern sections of the city to the treatment works by the lake. At that time, this was tricky undertaking with excavation by hand through water-bearing alluvial materials. Tunnel depths were up to 45m and compressed air was utilised as support.

As part of the environmental assessment for future expansion work, video inspections discovered a damaged section within the Coxwell Trunk sewer. The damaged section was close to residential properties and was of obvious concern to the City of Toronto. The City of Toronto considered it prudent to affect a repair to this section as quickly as possible. With the system running close to capacity, it was not possible to enter and repair in a reliable and cost-effective manner, and consequently, an emergency bypass tunnel was designed.

The bypass involves a short section of equivalent size tunnel running 500m around the damaged section of sewer. The tunnel was driven in full EPB as a one pass system with a precast concrete segmental liner. McNally Construction Ltd. was the successful proponent for the $30M Canadian contract. The contract is a design-build with Aecom Canada as the Designer and Hatch Mott Macdonald acting as project managers for the City. (Vince Luongo and Steve Skelhorn 2011).

7 CONCLUSION

This paper presented the application of GFRP bars in three different tunnel projects in reinforcing the soft-eyes. The soft-eyes were design according to CAN/CSAS806-02 “Design and construction of building components with fiber reinforced polymers.” Based on the observations at field and discussion presented herein the following concluding remarks can be drawn:

- In this investigation High Grade GFRP straight bars (60 GPa) and medium Grade (50 GPa) GFRP circular ties were used successfully in soft-eye tunnel application.

Figure 11. Overview of the GFRP Soft-Eyes and steel cages, (The Coxwell Sewer Shaft).

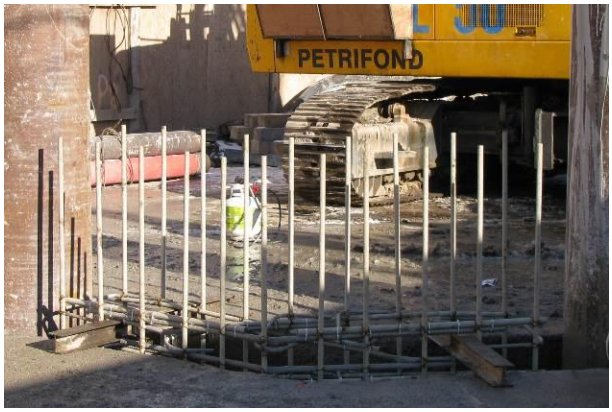


Figure 12. Overview of the GFRP angled cage in the caisson, (The Coxwell Sewer Shaft).

- This successful application shows the effective usage of the GFRP reinforcing bars in tunnel structures. This shows a great advancement in this field.
- Using GFRP bars as reinforcement in the diaphragm wall or in the bore piles has proven to be the most competitive in many situations to start or receive a TBM in an excavation shaft.
- GFRP bars can be cut with 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 fibre bars are split in small pieces which do not harm slurry pipes.
- No major problems or any un-expected performance-associated troubles appeared during the construction or after being in service for months.

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9 REFERENCES

American Concrete Institute (ACI). (2001; 2003; 2006). Guide for the design and construction of concrete reinforced with FRP bars, ACI 440.1R-01;03; 06, Farmington Hills, Mich.

American Concrete Institute (ACI). (2004). Guide test methods for fiber reinforced polymers (FRPs) for reinforcing or strengthening concrete structures, ACI 440.3R-04, Farmington Hills, Mich.

Canadian Standards Association (CSA). (2000). “Canadian highway bridge design code.” CAN/CSA-S6-00, Rexdale, Toronto.

Canadian Standards Association (CSA). (2002). “Design and construction of building components with fiber reinforced polymers.” CAN/CSAS806-02, Rexdale, Toronto.

Canadian Standard Association (CSA). 2006. Canadian Highway Bridge Design Code. CAN/CSA S6-06, Rexdale, Ontario, Canada, 788.

Canadian Standards Association (CSA). (2006-Edition 2010). “Canadian highway bridge design code—Section 16, updated version for public review.” CAN/CSA-S6-06, Rexdale, Toronto.

Canadian Standards Association 2010, CAN/CSA S807-10 “Specification for fibre-reinforced polymers, Canadian Standards Association, Rexdale, Ontario, Canada, 44 p.

Benmokrane, B., Wang, P., Ton-That, T. M., Rahman, H., and Robert, J. F. (2002). “Durability of glass fiber-reinforced polymer reinforcing bars in concrete environment.” J. Compos. Constr., 6(3), 143–153.

Benmokrane, B., El-Salakawy, E.F., Desgagné, G., and Lackey, T. (2004). "Building a New Generation of Concrete Bridge Decks using FRP Bars." Concrete International, the ACI Magazine, Vol. 26, No. 8, August, pp. 84-90.

Benmokrane, B., El-Salakawy, E., El-Ragaby, A., and Lackey, T. 2006. Designing and Testing of Concrete Bridge Decks Reinforced with Glass FRP Bars. Journal of Bridge Engineering, 11(2): 217-229.

Benmokrane, B., El-Salakawy, E., El-Ragaby, A., and El-Gamal, S. 2007. Performance Evaluation of Innovative Concrete Bridge Deck Slabs Reinforced with Fibre- Reinforced Polymer Bars. Can Jour of Civil Eng, 34(3): 298–310.

El-Salakawy, E.F., and Benmokrane, B. (2003). "Design and Testing of a Highway Concrete Bridge Deck Reinforced with Glass and Carbon FRP Bars." ACI Special Publication, Field Applications of FRP Reinforcement: Case Studies, SP-215-2, pp. 37-54. (Editor’s invitation).

ISIS Canada (2001; 2006; 2007). “Reinforcing concrete structures with fiber reinforced polymers.” ISIS-M03-2001; 2006; 2007, The Canadian Network of Centers of Excellence on Intelligent Sensing for Innovative Structures, Univ. of Winnipeg, Manitoba, Canada.

IMIA Working Group Paper WGP 60 (09) Tunnel Boring Machines

Marc Schürch and Peter Jost “GFRP Soft-Eye for TBM Breakthrough: Possibilities with a Modern Construction Material” International Symposium on Underground Excavation and Tunnelling 2-4 February 2006, Bangkok, Thailand

Vince Luongo and Steve Skelhorn 2011 “Permanent Slurry Walls Used in Toronto’s Deepest Shaft to Fix the Coxwell Emergency Bypass” DFI-Use of Structural Slurry Wall for Permanent Structures August 10th, 2011(Toronto, Canada).

NOTATION

A_{fv} = total cross-sectional area of shear reinforcement, mm^2
b_w = beam width, mm
c = neutral axis depth, mm
d = distance from extreme compression fiber to centroid of tension reinforcement, mm
E_{fl} = modulus of elasticity of longitudinal reinforcement, MPa
E_{fv} = modulus of elasticity of shear reinforcement, MPa
E_s = modulus of elasticity of steel, MPa
f_c = compressive strength of concrete, MPa
M_f = factored moment at a section, N·mm
s = spacing of shear reinforcement, mm
V_c = factored shear resistance provided by concrete, N
V_f = factored shear force at section, N
V_{FRP} = factored shear resistance provided by FRP shear reinforcement, N