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Design and Construction of the First Worldwide Concrete Water Tank Chlorination Totally Reinforced with GFRP Bars

Hamdy M. Mohamed[1], and Brahim Benmokrane[2]
[1] Postdoctoral Fellow, Dept. of Civil Engineering, University of Sherbrooke, Quebec, Canada.
[2] Canada & NSERC Research Chairs Professor, Dept. of Civil Engineering, University of Sherbrooke, Quebec, Canada.

Abstract: This paper presents the design procedures, construction details, testing, and monitoring results of the world's first RC water tank chlorination totally reinforced with glass-fiber-reinforced polymer (GFRP) bars. The project is located in Thetford Mines, Quebec, Canada. The tank is considered as one of the most important components in the city's new water treatment plant. The tank's volume capacity is over 2500 m3 and its walls are 4650 mm high. The foundation, vertical walls, and top slab were totally reinforced with GFRP bars. The tank was designed for satisfying the serviceability and strength criteria in CAN/CSA S806-12, ACI 440.1R-06, and ACI 350/350R-06. The tank is well instrumented at critical locations with fiber-optic sensors to collect strain data. Site inspection showed that the tank performed very well and was able to withstand applied loads without problem or leaking during the leakage test, and 8 months under the service condition.

1. INTRODUCTION

Electrochemical corrosion of steel stands out as a major cause of the deterioration of civil-engineering infrastructure. RC tanks, one of the most important structural facilities in the water and wastewater treatment plants (WWTPs), are usually subjected to a uniquely difficult environment in which corrosion poses exceptional challenges. These concrete tanks deteriorate faster than any other structure because of direct and permanent exposure to aggressive chemical environments. Yet the need to protect them is often identified only after significant deterioration has occurred. For years, containment designers have tried to achieve crack-free concrete to eliminate the corrosion problem. Techniques have included specific special mix designs, low water/cement ratios, many different admixtures, special aggregates, and supplementary cementitious materials, all with limited success. The use of halogens such as chlorine in disinfecting drinking water and treating wastewater, as well as ozonation, has a devastating effect on reinforcing steel products, whether they are black, galvanized, epoxy-covered, or even stainless-steel elements. While the chlorine remains the primary oxidant, other than oxygen (aeration) in chemical treatment methods is considered a corrosive agent in water. Evidently, water must be disinfected and of appropriate quality before being made available to the public. The subject of chloride-induced corrosion of steel reinforcement is very complex and depends on many factors such as concentration, temperature, and pH. Only careful selection of reinforcing materials can significantly prevent the detrimental effects of corrosion when reinforcement is exposed to aggressive products. So, the challenge facing structural engineers and municipalities is to design concrete tanks using noncorrosive materials such as fiber-reinforced-polymer (FRP) reinforcing bars.

In the last decade, there has been a widespread application in using noncorrosive FRP reinforcing composite bars for concrete structures due to their enhanced properties and cost-effectiveness. Known to be corrosion resistant, FRP bars provide a great alternative to steel reinforcement. FRP materials in general offer many advantages over 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). Since glass FRP (GFRP) bar is more economical than other available types of FRP bars (carbon and aramid), it is more attractive for infrastructure applications and to the construction industry. GFRP bars have been used extensively in different infrastructure 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 (Mohamed and Benmokrane 2012a). Many significant developments from the manufacturer and various researchers as well as in design codes, along with numerous successful installations, have led to a much higher comfort level and exponential use by designers and owners. 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 its corrosion-protection policy. That notwithstanding, to date, there have been no field applications reported in the literature on using FRP bars in RC tanks to resolve expansive-corrosion issues.

This paper presents the world's first field application of FRP bars in a concrete tank for a water treatment plant. Design and construction details of this tank are used to illustrate code requirements, tank analysis, design details, and construction of FRP-RC tanks. The tank was instrumented at critical locations to monitor cracks and strain behavior during a leakage test prior to backfilling (filling the tank with water). It is also intended to assess the in-service performance of the FRP-RC tank after several years after operation.

2. TANK DESCRIPTION

The Figure 1 presents the general overview of the plant. Thetford Mines decided to use noncorrosive FRP reinforcing bars in chlorine contact part to extend the tank's service life, reduce maintenance costs, and improve life-cycle cost efficiency of the new plant. The tank's structural system is underground, rectangular, resting on rock and completely buried with compacted fill soil around the walls. The surface area of the top slab is buried 600 mm of uncompact fill-soil. The vertical walls support the tank's cover slab and rest on a RC raft foundation. The tank's volume capacity is approximately 2500 m^3; the walls are 4650 mm high and the tank measures 24.0 m in with by 23.0 m in length. The tank is designed to include two closed cells (C_1 and C_2) with a continuous vertical wall (W_M) in the middle of the tank, (see Figure 1). Each cell is divided to create two zones with a non-continuous interior vertical wall (W_I). The clear spacing between these walls is 5475 mm. The thickness of the exterior and middle walls (W_E and W_M), top floor slab, and foundation is constant at 350 mm, while the thickness of the interior walls (W_I) is 300 mm.

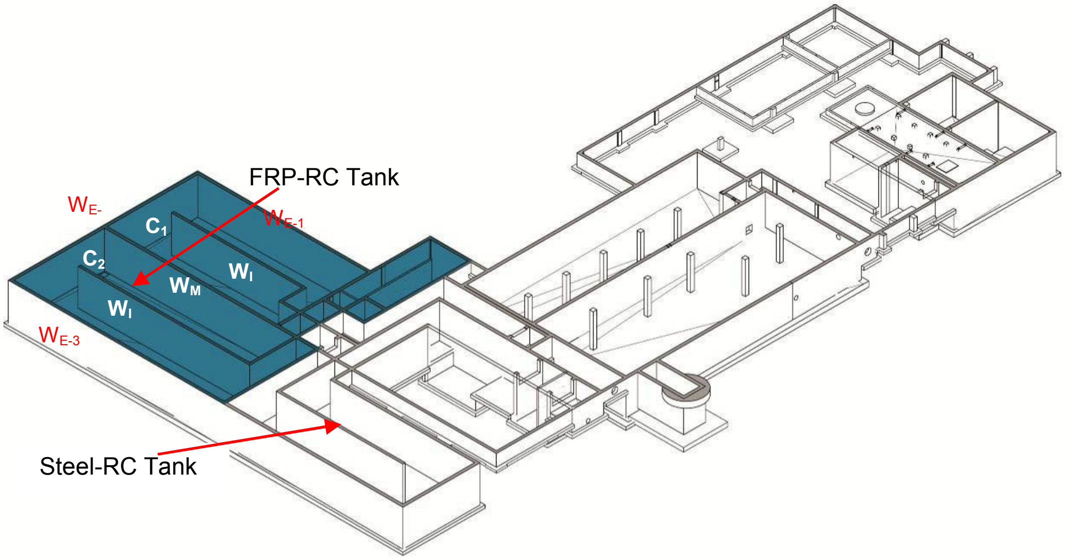

Figure 1: Overview of the water treatment plant

3. GFRP BARS USED IN THE TANK

Sand-coated GFRP bars were used to reinforce the three structural elements of the tank, foundation, walls, and cover slab. The bars were made of continuous E-glass impregnated in a vinylester resin using the pultrusion process as manufactured by a Canadian company [Pultrall Inc.]. The glass fibers give the bar mechanical strength, while the resin matrix (resin, additives, and fillers) provides corrosion resistance in harsh environments. The GFRP bars had a sand-coated surface to enhance bond performance between the bars and surrounding concrete, (see Figure 2). Two grades of these bars were used: Grade III and Grade II as classified in the CAN/CSA S807-10 according to Young's modulus (60 and 50 GPa, respectively). Grade III and II GFRP bars were used as the main and secondary reinforcement, respectively, in tank walls, cover slab, and foundation. Moreover, two bar diameters were used in the tank design: No. 15 and No. 19 (nominal cross-sectional area of 199 and 284 mm^2, as indicated in CAN/CSA S807-10). The mechanical properties of the GFRP bars are summarized in Table 1, as provided by the manufacturer. Considerable research efforts have been deployed in the past decade to assess the suitability of FRP reinforcement in reinforced-concrete structures (Robert et al. 2009). The work of these researchers has highlighted the short- and long-term performance of FRP-reinforced-concrete structures and the durability of FRP reinforcing bars subjected to different conditions, including immersion in alkaline solution, sustained tensile stress, elevated temperature, and freeze–thaw cycles. The results of these studies have revealed that the effect of the aforementioned conditions had no significant effect on the tensile strength of the GFRP bars for a service life exceeding 100 years.

Table 1. Properties of the GFRP reinforcing bars used in the tank

Bar diameter (mm)	Grade	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Ultimate Tensile Strain (%)
15	II	934	55.4 ±2.5	1.69
15	III	1105	64.7 ±2.5	1.71
20	III	1059	62.6 ±2.5	1.69

Note: ±XX_standard deviation.

Figure 2: Straight and bent sand-coated GFRP-reinforcing bars as shipped to the site

6. TANK DESIGN

6.1 Codes

The design was made according to the CAN/CSA S806-12 (2012) *Design and Construction of Building Components with Fiber-Reinforced Polymers*, CAN/CSA-A23.3-04 (R2010) - *Design of Concrete Structures*, ACI 440.1R-06 *Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars*, and ACI 350/350R-01/06 (2001/2006) *Code Requirements for Environmental Engineering Concrete Structures and Commentary*. The loads were calculated according to the *National Building Code of Canada* (NBCC 2005). The tank was designed to determine all the possible loading conditions resulting from water pressure and soil load on the walls and foundation; dead and live loads on the top slab were considered. According to ACI 350, the full effects of the soil loads and water pressure were considered without the benefit of resistance of the loads which could minimize the effects of each other. The design involved normal-weight concrete with a target 28-day compressive strength of 35 MPa.

6.2 Structural Analysis and FRP Reinforcement Details

The reinforced concrete tank is a combination of walls, foundation, and top slab. The vertical walls and foundation are rigidly connected together to form a monolithic frame. The top slab was designed based on one-way loading action in the short direction, as statically indeterminate continuous four equal-spans on a hinged support. Moreover, the loading action on the walls combined with the foundation was considered one-way in the short direction since the water pressure is resisted by vertical bending moments in the walls. Figure 3 shows a half vertical section of the outer and interior walls, foundation, and top slab with the axis-symmetric reinforcement details. The tank was designed based on serviceability and the ultimate limit state for FRP reinforcement requirements, while the thickness was determined using the working stress design, as recommended by ACI 350. The size of reinforcing FRP bars was chosen with the knowledge that cracking could be better controlled by using a larger number of small diameter bars rather than fewer larger diameter bars (ACI 350). Several bars at moderate spacing are much more effective in controlling cracking than one or two larger bars of equivalent area. For these reasons, No. 15 bars were used extensively in designing the tank, with spacing ranging from 90 mm to 180 mm. Since No. 19 bar was used only in one section in the foundation, since the maximum observed moment required a high reinforcement ratio.

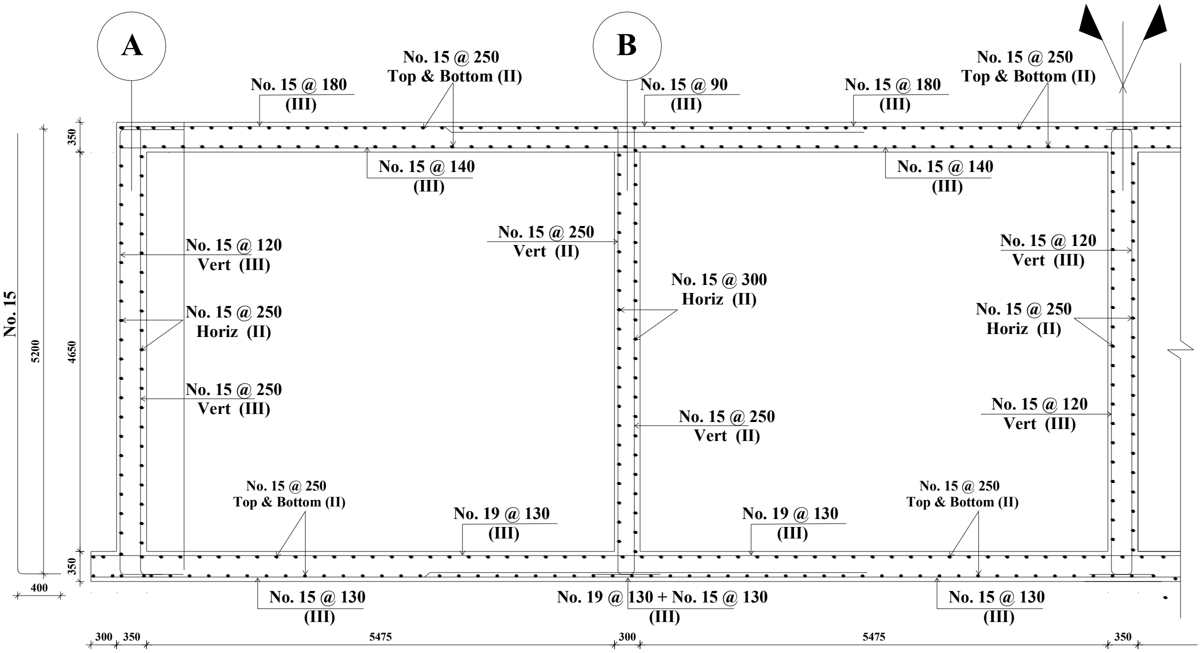

Figure 3: FRP-reinforcement details for the main vertical section in the tank.

7. TANK CONSTRUCTION

Tank construction started and was completed in February and July 2012, respectively. The soil under the foundation is rock. Site excavation began in February, with soil, rock, and other materials being removed, typically with heavy earthmoving equipment such as excavators and bulldozers. The depth of excavation was around 5.5 m, to create a level, clean area to work, with the foundation being established in the excavated area. The FRP bars were delivered to the site in mid-March. The placement of GFRP reinforcement for the bottom and top foundation mat as well as concrete casting and curing were started and finished by the end of March. Continuous plastic chairs were placed in the longitudinal direction at 0.7 m intervals under the bottom reinforcement mat to support the FRP bars and maintain the required clear concrete cover. In the case of the top mat, single chairs at 0.9 m intervals in both directions were used. Through April and May, the construction was stopped in the FRP-RC tank and shifted to complete and cast the top slab of the steel-RC tank. Thereafter, wall construction started in May 27, 2012, with the installation of the interior and exterior mats of the FRP reinforcing bars (vertical and horizontal bars). After that, the formwork, casting, and curing of the walls was started and completed on June 5, 2012. Figure 4 shows the formwork, FRP-vertical and horizontal reinforcement of the vertical walls, before and after casting and during the different construction stages. The day after the wall were cast, all the formwork for the interior walls on both sides was removed, while the exterior formwork for the outer walls was maintained and used through all the construction stages of the top slab. The formwork for the top slab started directly after removing the wall formwork and was finished in mid-June. The placement of GFRP reinforcement for the bottom and top mat of the top slab and concrete casting was started and finished by June 22, 2012. In addition, continuous plastic chairs were placed in the longitudinal direction at 0.8 m intervals under the bottom of the top reinforcement mat to support the FRP bars and maintain the required clear concrete cover. After casting, the slab was cured for 10 days, with the formwork being completely removed 4 days later. Figure 5 shows the FRP-RC top slab. Following that, cleaning work and leveling of the top surface of the foundation with cement mortar inside the tank were completed in the mid-July to start filling the tank with water.

Figure 4: Overview of vertical walls.

Figure 5: Overview of top slab during casting.

8. TANK INSTRUMENTATION

The FRP-RC tank was instrumented at critical locations to measure internal strain data using fiber-optic sensors (FOSs). The objective of using FOSs was to allow for the long-term monitoring of the tank. The wall and top slab were instrumented with 6 and 10 FOSs, respectively, at different locations. One of tank's exterior walls was chosen to be instrumented to collect the strain data at maximum moment location for the two loading conditions: water and earth pressure. Three FOSs were glued on three vertical GFRP reinforcing bars on each side of the wall and interior and exterior mat. The GFRP bars were instrumented at the structural laboratory of the University of Sherbrooke. Thereafter, the bars were shipped to the construction site where they were installed at the designated location during the construction stage of the wall. The interior and middle walls were not instrumented since the water pressure acts on both sides. It is of interest to mention that an FOS can measure strain data in the range of positive and negative 2500 microstrains. The benefit of this lies with collecting the tension and compression strain in the FRP bars, since, in the case of exterior wall, the moment is reversible due to the opposite effect of earth and water pressure. Figure 6(a) shows the GFRP bars instrumented with FOSs.

Figure 6: Preparation and instrumentation of GFRP bars

The ten FOSs in the top slab were distributed along the mid-span section between the walls for the positive moment (top and bottom mat) and over the wall for the negative moment (top and bottom mats). These sensors were glued on the transverse GFRP reinforcing bars at the locations of expected maximum stresses. These bars were prepared with FOSs in the site, because the bar length ranged from 9.0 to 16.0 m, and it was difficult to protect and ship these bars with FOSs from the university to the site. All the FOS wires in the wall and slab were collected and passed at one point in the top surface of the top slab. Eight-channel data-acquisition systems were used to collect FOS readings at the different stages of construction.

9. WATER LEAKAGE TEST OF THE TANK

The leakage test was performed three days immediately after the formwork for the top slab was removed and before any backfilling. The steel and FRP RC tank were tested by the contractor and witnessed by the consulting engineer. As mentioned before, the tank had two cells, so each cell should be considered a single tank and tested individually. One of these cells was filled up completely with water to check for leakage; the other cell remained empty. After finishing the test on one side of the tank and checking all visible cracks, the water transferred to the other cell. Figure 7 shows the tank overview during the leakage test of one cell. The water was kept at test level for three days prior to the actual test. The exterior wall surfaces of the tank were inspected while the tank was being filled.

Figure 7: Overview of the completed tank through the leakage test and prior to backfilling

9.1 Flexural Cracks

Visual inspection of the tank over three days indicated that the leakage test did not induce flexural horizontal cracks in all the walls. No water leakage was observed, which would indicate flexural crack leaking. This can be attributed to the compression zone developed in one side of the wall section as a result of flexural stresses, which could effectively prevent leakage through cracks regardless of crack width. At this juncture, it is of interest to mention that the cracking moment resistance for the 350 mm thick wall was 75 kN.m/m. This moment is almost over the service moment in the wall resulting from the water pressure during the leakage test. The walls were designed to minimize the crack width resulting from the one-way load action of the water pressure in the vertical direction. This means that the flexural cracks are not of concern with regard to leakage, because the liquid passage through the depth of the section is obstructed by the presence of uncracked concrete in the compression zone. Nevertheless, the compression zone depth should be controlled for limiting liquid loss through concrete permeability. This result is consistent and in a good agreement with the research work and experimental test results conducted by Ziari and Kianoush (2009).

9.2 Shrinkage and Restraint Cracks

During the leakage test, a site inspection showed that the water tank developed limited vertical shrinkage cracks, which became leaks that did not self-seal. Such cracks are common and expected in the liquid tank at the first stage of service loading. These are minor indications and have no real structural impact on the tank. To control leakage in water tank, cracks cannot be prevented, but must be minimized, and crack width should be kept below a certain limit under service loads, (Ziari and Kianoush 2009). The leakage test results for the FRP tank indicated that the number of observed cracks in the exterior surfaces of walls W_{E-1}, W_{E-2}, and W_{E-3} were 6, 5, and 7, respectively. The cracks were perpendicular to the direction of the maximum principle stress induced by moment. The cracks extended from the base and propagated up to the full height of the wall. At the corner of the tank, one inclined crack in each wall was observed, propagating from the base toward the corner edge at an angle of about 45°. This crack stopped below wall mid-height. The engineer described the observed cracks as “minor” leaks, as was expected for this structure. The crack width was measured using a microscope, with the measured widths ranging from 0.06 to 0.18 mm, which is less than the allowable limit (ACI 350). Figure 8 shows the crack patterns through one of the exterior walls (W_{E-1}). On the other hand, the leakage test was conducted for the steel-tank one month previously. Despite the fact that the shrinkage reinforcement used in the steel tank was higher than that used in the FRP tank (steel bar No. 15 @225 mm both sides versus GFRP bar No.15 @ 250 mm on both sides). The leakage test results for the steel tank, however, indicated that the number and widths of the observed cracks in the exterior surfaces for similar wall dimensions were insignificantly higher than that observed in the FRP tank. The measured crack widths ranged from 0.097 to 0.24 mm.

Figure 8: Overview of the general cracking behavior during the leakage test of the FRP tank

After completing the leakage test for each cell in the tank, the engineer decided to repair the cracks causing the leakage using an external injection system in each wall. Crack injection has been performed for many years. The injection procedure would entirely fill the crack, from front to back. Injection has proved to be effective for filling cracks from 0.002 to 50 mm in width. All the cracks were repaired using pressure injection of polyurethane foam sealant after inserting the stainless-steel injection ports around the cracks in the vertical direction. Figure 8 shows crack leaking, stainless-steel injection ports, and foam sealant over the crack. This material is water activated for use in wet environments, so there was no need to empty the tank. The injection sealant continues to work for considerable time after application. So, if there is future movement, the sealant will expand and contract compensating for it. After treatment, the leaking stopped and the wall started to dry out. Thereafter, the construction work for the backfill was started immediately after ensuring no leakage. The exterior walls were buried with compacted fill soil; a vibratory-plate compactor was used for compaction. Finally, the surface area of the top slab was buried under 600 mm of uncompacted fill soil.

10. WALL TENSION STRAIN

Figure 9 shows the strain measurements from the FOSs attached to the GFRP bars for the interior and exterior vertical reinforcement. The initial strain readings were recorded a few hours before casting (zero point at the x-axis). After casting, the strain readings were recorded daily for one week. Following that, the 6 wall FOSs were monitored each week. Therefore, the reported strain values in the first 10 days represented concrete shrinkage. Moreover, the high temperature due to cement hydration at early age could be observed. Figure 9 shows the sudden variation in tension strains from compression to tension strain, as a result of the wall moment due to water pressure. The maximum tension strain ranged from 40 to 60 microstrains during the leakage test and after the backfilling was initiated. The measured values indicate that the strains in the wall were insignificant, as it represented less than 1.0 % of the ultimate strain of the GFRP bars. This can be attributed to two reasons. First, considering the straining action of these forces and determining the maximum compression and tension stresses on the wall, the results will be approximately equal to -0.8 and 0.5 MPa, respectively. These values are insignificant compared to the strength capacity of the wall cross section (350 mm). On the other hand, the cracking moment of the wall's cross section is higher than that the actual moment during the leakage test. This was confirmed from the site inspection during the leakage test, since no flexural cracks were observed. The backfilling work started immediately after the shrinkage cracks were repaired, making it possible to release the water pressure given the opposite action of the soil pressure. Yet the strain in the FRP bars of the exterior mat continued to increase up to the addition of uncompacted soil over the top slab, the tension strain decreased and stabilized as the result of the opposing action of the water and earth pressures, in addition to the weight of the soil on the top slab.

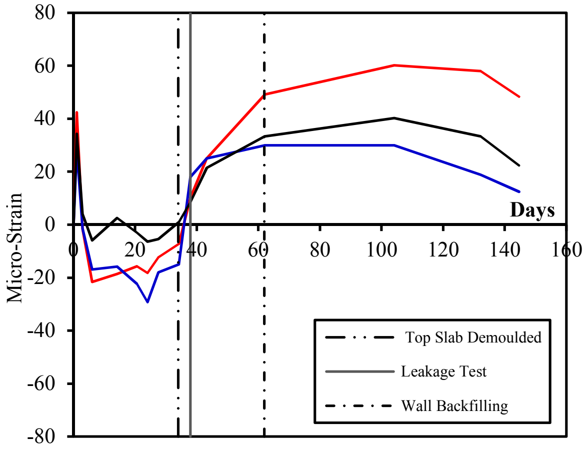

Figure 9: Measured strains in the FRP vertical reinforcement in the wall ($W_{E\text{-}1}$).

3. CONCLUSIONS

This successful field application shows the effective usage of GFRP reinforcing bars in a reinforced-concrete tank for a water treatment plant the first time in the world. The structural performance of this first application of its type and scale, based on the monitoring and continuous observations, was expected. No major problems or any unexpected performance-associated difficulties appeared during construction or after 8 months of service. This application opens the door to the major application of FRP reinforcing bars in reinforced-concrete water tanks in North America and across with world. Reinforcing concrete water tanks with GFRP bars would extend the life of such structures to 100 years or more compared to steel-reinforced concrete, which needs major restoration after 25 years.

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