The Heart of Innovation in SPARK, Saudi Arabia

The first bridge deck reinforced with GFRP bars in the GCC

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King Salman Energy Park (SPARK), an industrial city in Saudi Arabia, is a multibillion-dollar development project positioned as an industrial ecosystem and energy hub that will attract and host vibrant and internationally recognized energy organizations. SPARK is also a leading contributor to Saudi Arabia's Vision 2030 initiative in its efforts to support the Kingdom's diversification goals. As a part of these efforts, SPARK has announced the deployment of multiple highly innovative and sustainable construction solutions. Glass fiber-reinforced polymer (GFRP) bars, as a reinforcement in concrete structures, are one of these leading technologies to help SPARK obtain Leadership in Energy and Environmental Design (LEED) Silver certification.

The industrial city consists of three main zones, including an industrial community, a nonindustrial community, and a logistic zone. The city is strategically positioned along the proposed Gulf Cooperation Council (GCC) Line, also known as the Gulf Railway, which will connect the six GCC member states in Eastern Arabia for ease of access and trade with local, regional, and international markets.

The SPARK bridge (Fig. 1) was built in Buqayq to direct vehicular traffic to the main entrance of the industrial city. Constructed in 2020, the 71 m (233 ft) long bridge with precast/prestressed concrete girders and a concrete deck reinforced with GFRP bars is the first of its kind in the GCC. Located just 24 km (15 miles) from the Arabian Gulf coast, the bridge is exposed to harsh environmental conditions characterized by high ambient salinity, high humidity, and windblown salt-contaminated dune sands. In such an environment, GFRP bars eliminate the risk of future deterioration of the concrete due to corrosion.

SPARK Bridge Team

The industrial city is being developed, operated, and managed by Saudi Aramco and the Saudi Authority for Industrial Cities and Technology Zones (MODON). Saudi Aramco's Consulting Services Department (CSD) was engaged during the development of design engineering

Fig. 1: SPARK bridge after completion

There are more than 617,000 traditional bridges in the United States, of which 259,000 (42%) are at least 50 years old, and 46,154 (7.5%) are considered structurally deficient.[1] Rehabilitation costs for these bridges are estimated at 125 billion USD.[1] Prevailing harsh environmental and weathering conditions cause steel reinforcement to corrode, leading to cracking and damage to reinforced concrete structures, such as concrete pavements, foundations, sidewalks, and bridges. To construct more durable and sustainable infrastructure that can withstand adverse exposure conditions, corrosion-free nonmetallic materials such as glass fiber-reinforced polymer (GFRP) bars can be used as a viable, more durable, and sustainable alternative to steel reinforcement.[2]

Currently, in North America, there are more than 267 bridges designed and built using fiber-reinforced polymer (FRP) bars—65 in the United States and 202 in Canada.[3]

To advance knowledge and applications of nonmetallic building materials, including GFRP reinforcement, Saudi Aramco collaborated with ACI to establish NEx: An ACI Center of Excellence for Nonmetallic Building Materials. Several global GFRP bar manufacturers, including IKK Mateenbar, are active members of NEx.

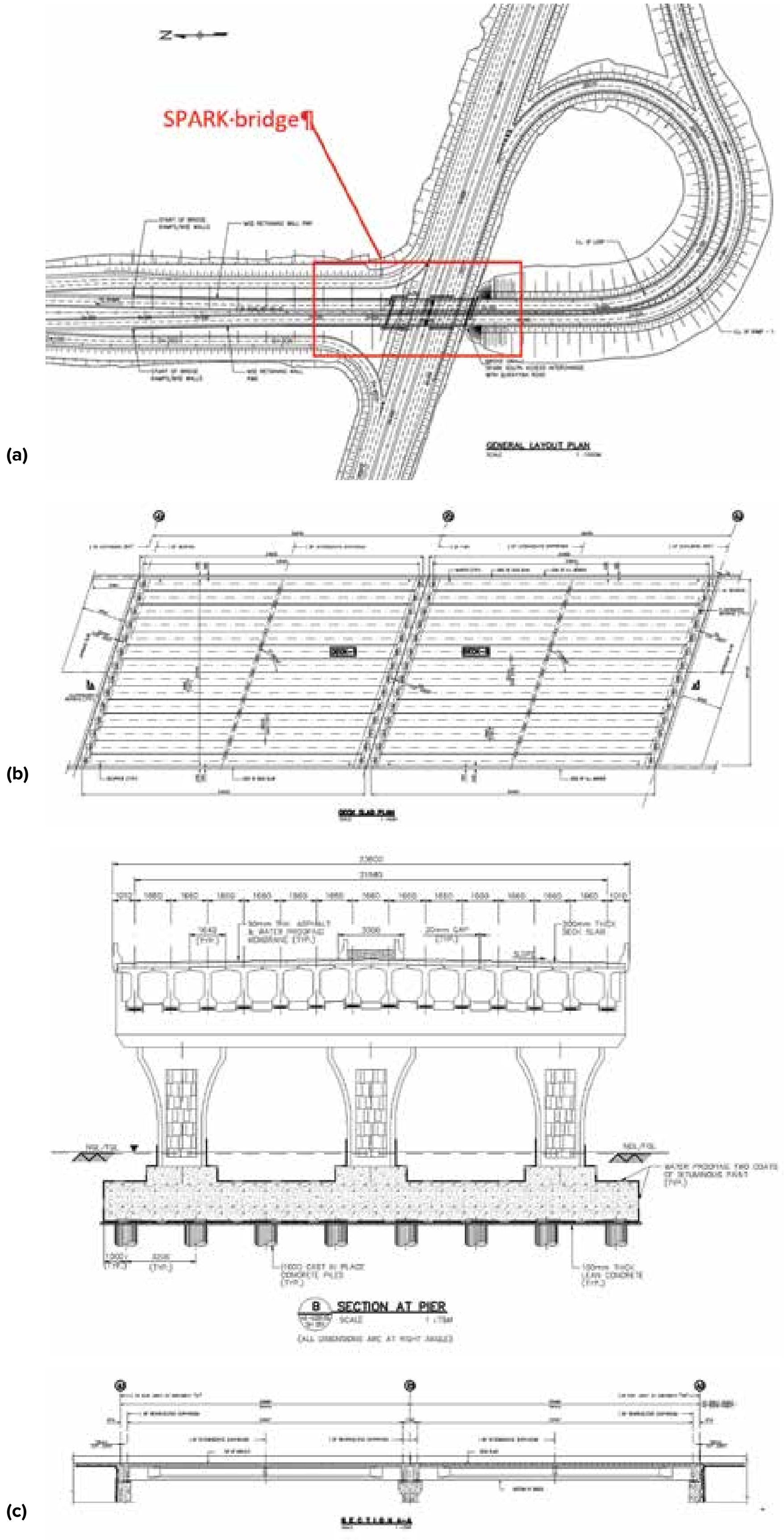

Fig. 2: Bridge design drawings: (a) project master plan; (b) bridge plan view; and (c) bridge section view (from Reference 10)

packages and specifications for the bridge. The Project Management Team (PMT) of Saudi Aramco was responsible for overseeing all aspects related to the construction of the bridge and ensuring compliance with the latest engineering standards and material specifications mandated by Saudi Aramco. The structural design for the SPARK bridge was carried out by Saudi Arabian Parsons Ltd. (SAPL), an international design firm that specializes in civil engineering, architecture, and project management. The bridge construction was completed by Shibh Al-Jazira Contracting Company (SAJCO), a construction company that specializes in delivering high-quality construction solutions for a wide range of civil projects. The manufacturer of GFRP bars for the project was IKK Mateenbar, a leading producer of GFRP bars located in Dammam, Saudi Arabia. IKK Mateenbar was previously known as Pultron Composites.

Concrete Reinforcement

Saudi Arabia is predominantly using epoxy-coated reinforcement (ECR), which meets the latest Ministry of Transport (MOT) standards for bridges. Saudi Aramco is now leading the way in Saudi Arabia by showcasing the benefits and advantages of using GFRP bars instead of ECR. The use of nonmetallic materials in corrosive environments eliminates maintenance costs and increases the service life of concrete structures by more than 100 years.[2] These advantages align with Saudi Arabia's Vision 2030 goals of using more sustainable materials to diversify the Kingdom's economy and reduce energy consumption to lower total CO_2 emissions.

Saudi Aramco Standards

Saudi Aramco published a fiber-reinforced polymer (FRP) bar specification (12-SAMSS-027[4]) in 2017. That was followed by an engineering standard (SAES-Q-001[5]) incorporating FRP bars as a direct replacement for reinforcing steel bars and ECR in corrosive environments. FRP bars were mandated in various noncritical structural applications. These include, but are not limited to, slabs-on-ground, surface drainage channels, sidewalks, concrete pavements, and pipe sleepers. The use of FRP dowels at joints in concrete pavement and slab-on-ground applications, to limit restraint of expansion and contraction movements, was also permitted in the Saudi Aramco standards as a substitute for steel, epoxy-coated, and stainless-steel dowels. The standard also allows for adjustments in concrete mixture design, concrete cover, and concrete durability protection measures to further capitalize on the benefits of using FRP reinforcement. SAES-Q-001, published in 2023,[6] has expanded the use of FRP reinforcement to all concrete exposure conditions except for sulfur pits construction.

Conversion to GFRP Bars

The CSD initially proposed the use of ECR in the design of the SPARK bridge back in 2017. To promote the use of nonmetallic materials in structural applications, the CSD expanded the use of GFRP bars by including them in the superstructure of the bridge, knowing that it is a critical structural component exposed to a wide variety of dynamic vehicular loads. The design was subsequently revised to include GFRP reinforcement in the detailed design stage as a replacement for the traditional ECR in the bridge deck, approach slabs, and barriers. Helically grooved GFRP bars were chosen to be used on the project.

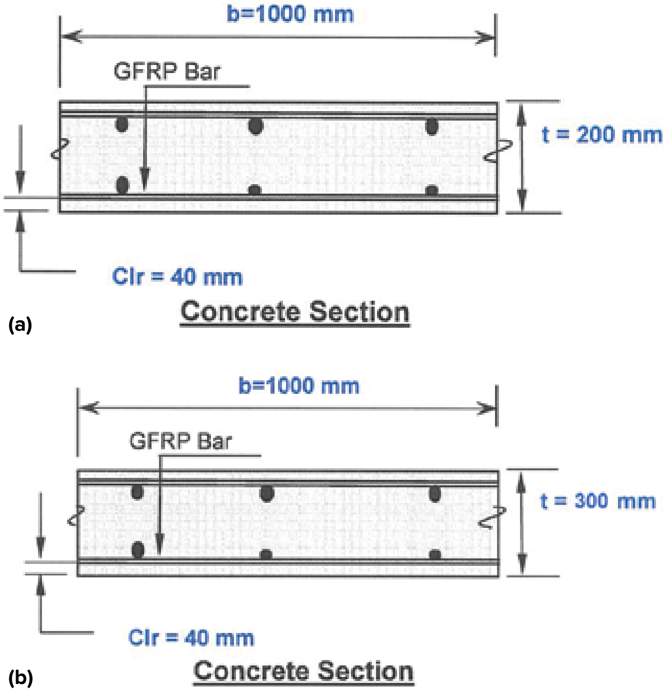

Fig. 3: Cross sections: (a) bridge deck; and (b) approach slab (from Reference 10)

Structural Design

The SPARK bridge was designed using AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete,[7] ACI 440.1R-15,[8] ASTM D7957/D7957M-17,[9] and 12-SAMSS-027.[4]

The SPARK bridge is a four-lane, two-span bridge with a clear span of 35.6 m (116.8 ft) and a width of 23.6 m (77 ft) (Fig. 2). The superstructure of the bridge comprises 14 adjacent precast/prestressed concrete bulb-tee girders and a reinforced cast-in-place concrete deck. The approach slab of the bridge measures 5.26 m (17 ft). The total surface area of the bridge is 1917 m^2 (20,634 ft^2). The reinforced concrete bridge deck and approach slabs have a depth of 200 mm (8 in.) and 300 mm (12 in.), respectively, and are reinforced with GFRP bars, as shown in Fig 3. The design criteria for the bridge per AASHTO LRFD[7] and vehicular live load as per the MOT Highway Design Manual (HDM)[11] included:

- Truck loading
  - Front axle with two wheels at 40 kN (9000 lb) and other axles with two wheels at 130 kN (29,225 lb), and
  - Distance from front axle to central axle of 4300 mm (170 in.) and distance from central axle to rear axle from 4300 to 9000 mm (354 in.);
- Lane loading
  - Uniformly distributed load of 20 kN/lane/m (1370 lb/lane/ft), and
  - Edge load of 150 kN (11,240 lb)/lane for moment and 220 kN (49,460 lb)/lane for shear;
- Hypothetical single axle load of 320 kN (71,940 lb);
- Concrete strength of 35 MPa (5080 psi) for the superstructure deck slab, New Jersey (NJ) barriers, and approach slab;
- GFRP bars with tensile modulus of elasticity of 40 GPa (5800 ksi) and tensile strength of 550 MPa (79,770 psi);
- Cement content of 400 kg/m^3 (674 lb/yd^3);
- Concrete cover of 40 mm (1.5 in.) for the bridge deck and approach slab and of 50 mm (2 in.) for the NJ barrier; and
- Shrinkage and thermal crack width limit of 0.513 mm (0.020 in.).[7]

To meet minimum serviceability and flexural strength requirements, the bridge deck was reinforced with two layers (top and bottom) of 16 mm (No. 5) GFRP bars spaced 100 mm (4 in.) apart as the main reinforcement. The top and bottom distribution bars were 16 mm GFRP bars spaced at 125 mm (5 in.) on-center. For the approach slab, which is a grade-supported slab, two layers of 22 mm (No. 7) GFRP main reinforcement spaced at 100 mm and 19 mm (No. 6) GFRP distribution reinforcement spaced at 125 mm on-center were provided. Concrete minimum temperature and shrinkage reinforcement checks were satisfied. A bridge barrier with a height of 1.1 m (3.6 ft) was also designed using GFRP bars. The 13 mm (No. 4) GFRP main reinforcement spaced at 125 mm and 13 mm horizontal reinforcement at a spacing of 150 mm were sufficient to resist the applied loads. GFRP bars were not used in the NJ barriers due to time constraints and procurement delays.

Durability

The SPARK bridge was originally designed with ECR to achieve a 75-year service life, as per the AASHTO bridge design standard.[7] The harsh environmental conditions in the region made the use of ECR unfavorable because deck slabs are more susceptible to developing wider cracks over time, which can lead to corrosion of steel. The frequent occurrence of sandstorms and high salt-contaminated water in the areas around the bridge would expose the concrete structure to high amounts of chlorides and sulfates, which can penetrate concrete and reach areas of the steel where the epoxy coating has been scratched during handling and installation. Because concentrated corrosion may occur in such areas, GFRP bars were used in several components of the bridge to eliminate corrosion-related maintenance costs and ensure a service life of over 100 years for the bridge deck.

Table 1:
ECR and GFRP option comparison

Applications	ECR*, tonne	GFRP†, tonne	Variance, tonne	Savings, %
Reinforcing bars				
Bridge deck slab	90.0	30.0	60.0	67
Approach slab	20.0	7.0	12.9	64
Total	110.0	37.0	72.9	66
Concrete volume, m³				
Bridge deck slab	370.0	335.0	35.0	10
Approach slab	80.0	75.0	5.0	6
Total	450.0	410.0	40.0	9

*ECR option concrete depth is 300 mm for the approach slab and 220 mm for the bridge deck

†GFRP option concrete depth is 300 mm (12 in.) for the approach slab and 200 mm (7.9 in.) for the bridge deck

Note: 1 tonne = 1.1 ton; 1 m^3 = 1.3 yd^3

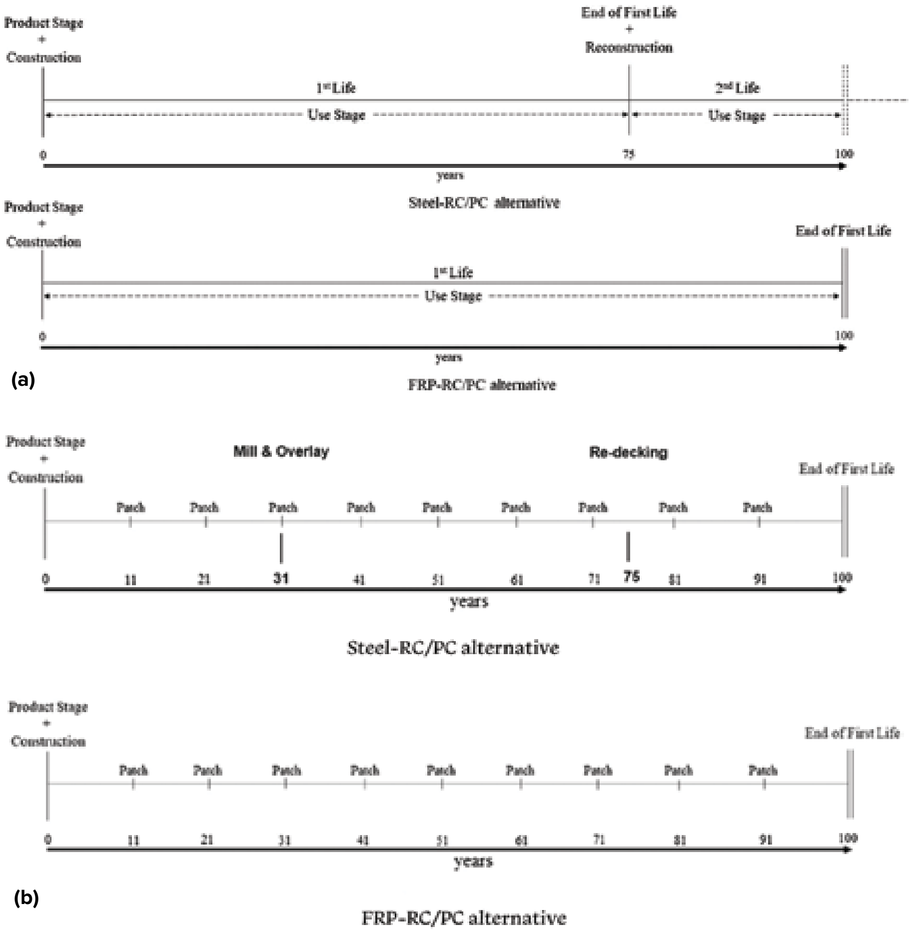

Fig. 4: Project life cycle: (a) service life; and (b) maintenance schedule (from Reference 12)

Initial Cost Comparison

In terms of total direct costs at the site, the GFRP bar option offered initial cost savings of about 2% compared with the ECR option. GFRP bars allowed reductions in concrete cover and a lower concrete grade, resulting in a total reduction of 40 m^3 (52 yd^3) in the quantity of concrete (see Table 1). While these savings were modest, additional indirect cost savings associated with the installation of GFRP bars included reduced staffing requirements and reduced rental costs required for renting lifting cranes. A similar study conducted for another Saudi Aramco project with GFRP bars, the Jazan Flood Mitigation Channel, showed high initial cost savings of over 21%.[2]

Project Life Cycle

A life-cycle analysis for this project was performed by SAPL using Life-365 (Version 2.2.3), a software program designed to estimate the service life and life-cycle costs of reinforced concrete structures exposed to chlorides. Several alternatives were investigated using the model, including traditional steel, ECR, and stainless-steel reinforcing bars. The Life-365 model did not include GFRP bars at that time. In a more recent study, a project life-cycle comparison was completed in 2019 for a bridge in Florida, USA, using the Life-365 software as shown in Fig. 4.[12] The results of this study were used as the basis for a direct cost comparison between ECR and GFRP bars (Fig. 5) for the SPARK bridge project. Prices sourced locally in Saudi Arabia for corrosion maintenance and patching measures were used as the basis for the cost comparison for a period of 100 years (see Table 2).

As per AASHTO standards, it is assumed that the ECR option and conventional steel option would have the same service life of 75 years.[7] For the ECR option, a cost attributed to proactive maintenance will be required every 10 years, with milling and an overlay required at year 31 and re-decking at year 75. The proactive maintenance cost every 10 years will be attributed to having to repair 10% (192 m^2 [2067 ft^2]) of the total surface area of the bridge at each cycle. The GFRP bar option offers a service life of 100 years.[12] A cost attributed to proactive maintenance will be included every 10 years, based on repairs to be performed on 2% (39 m^2 [420 ft^2]) of the concrete surface area, as a conservative measure to repair cracks as needed. Therefore, savings of just over 314,462 USD are anticipated with the GFRP option in the 100-year period.

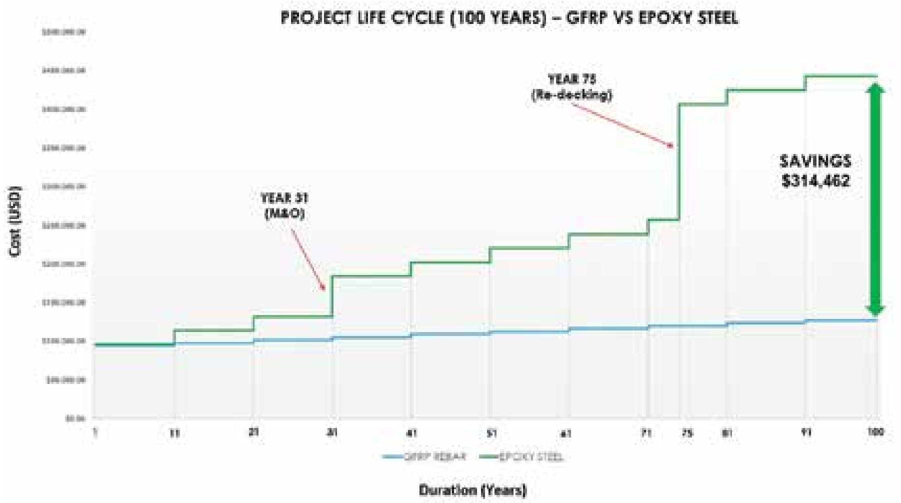

Fig. 5: Project life-cycle cost comparison between GFRP and ECR for 100 years

Conclusions

The success of the construction of a first bridge deck reinforced with GFRP bars in the GCC was the result of a coordinated effort, advocacy, and technical cooperation among the stakeholders in the supply chain and the development and alignment with international standards. This deployment has shown that the use of GFRP bars is a proven cost-effective and sustainable solution for the construction of bridge decks in the aggressive GCC environments.

Summary

The SPARK bridge was constructed in 2020 to support and direct vehicular traffic to the main entrance of the industrial city. The bridge deck and the approach slabs for the bridge were built

Table 2:
Project life-cycle cost comparison for 100 years based on market prices in Saudi Arabia in 2020

Year	Maintenance	GFRP, USD	ECR, USD	Savings, USD
11	Patching	3637*	18,183†	16,365
21	Patching	3637	18,183	16,365
31	Mill and overlay (half of design life for ECR)	3637	51,678‡	49,860
41	Patching	3637	18,183	16,365
51	Patching	3637	18,183	16,365
61	Patching	3637	18,183	16,365
71	Patching	3637	18,183	16,365
75	End of 75-year design life for ECR	0	150,053§	150,053
81	Patching	3637	18,183	16,365
91	Patching	3637	18,183	16,365
100	End of design life	—	—	—
Total		32,733	347,195	314,462

*Maintenance cost: 2% of bridge deck area every 10 years for the GFRP option

†Maintenance cost: 10% of bridge deck area every 10 years for the ECR option[13]

‡Cost for a total area of 1914 m^2 (20,602 ft^2)

§Cost for demolition plus cost of building a new bridge deck (steel, concrete, labor, and mill and overlay cost), for 25 years until year 100

Fig. 6: GFRP bar installation and concrete placement at the SPARK bridge

using concrete reinforced with GFRP bars in place of ECR (Fig. 6). The nonmetallic reinforcement is expected to reduce maintenance costs associated with exposure to the harsh environment existing at the bridge location and increase the service life of the bridge by more than 100 years.

GFRP bars have proven to be an economical option when compared to ECR in terms of initial cost, as presented by the results of this study. Since the construction of the SPARK bridge, a new design code for GFRP bars has been published by ACI—ACI CODE-440.11-22,[14] and it's expected to provide further design and cost savings for bridges to be constructed in the future.

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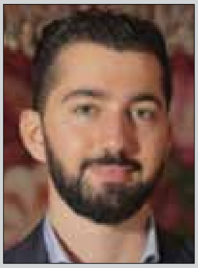

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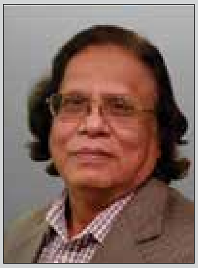

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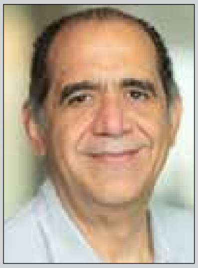

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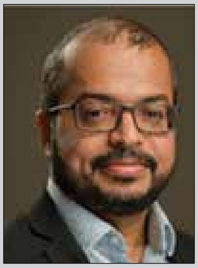

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