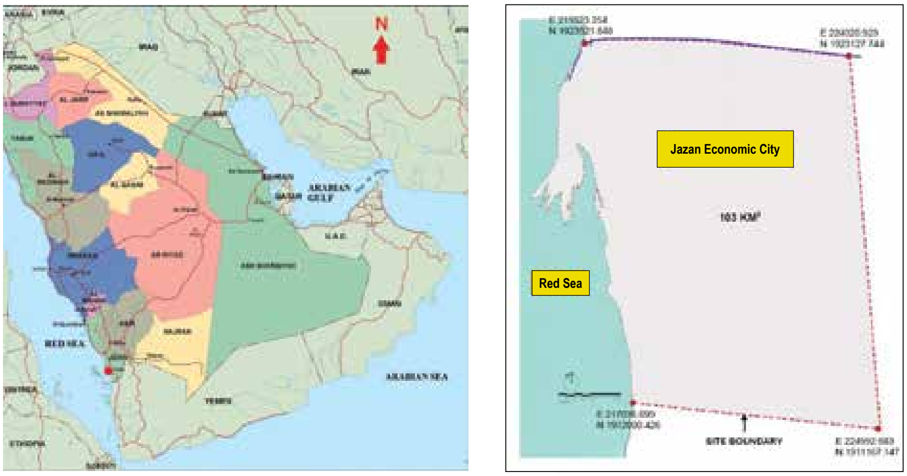
A Monumental Flood Mitigation Channel in Saudi Arabia

The 21 km long lining is the world's largest concrete structure reinforced with GFRP bars

by Eduardo A. Villen Salan, Muhammad K. Rahman, Sami Al-Ghamdi, Jihad Sakr, Mesfer M. Al-Zahrani, and Antonio Nanni

The world's largest concrete structure reinforced with glass fiber-reinforced polymer (GFRP) bars was completed recently in Saudi Arabia. The 21.3 km long flood mitigation channel (FMC) was constructed in southwest Saudi Arabia on the outskirts of the new Jazan Economic City (JEC) (Fig. 1). JEC is located about 725 km south of the city of Jeddah and 80 km from Jazan city. It covers an area of about 103 km^2 and has a 12 km long coastline on the southern end of the Red Sea. JEC is in close proximity to the main east and west trade routes to Europe, the Far East, and the Arabian Gulf. It is an advanced industrial zone equipped with a network of high-end facilities for heavy processing industries, including a 400,000 barrels-per-day oil refinery, hydrocarbon terminal facility, desalination plant, steel reinforcing bar plant, copper smelter, aluminum complex, a major seaport, and the world's largest integrated gasification combined cycled power plant.

This huge endeavor also includes the development of the area to accommodate actual and future companies that, under the light of the new refinery, will bring new products, services, and jobs. State-of-the-art infrastructure, combined with a favorable location on the Red Sea shipping route, is expected to transform the area into a major regional hub, contributing to the economic growth of the region and the Kingdom. A paramount project being undertaken in JEC is the construction of the JEC-FMC, running parallel to the north-south and east-west JEC boundaries.



(a) (b)

Fig. 1: Project location: (a) Jazan Economic City is on the coast of the Red Sea; and (b) the site boundary encloses an area of 103 km^2

The JEC-FMC is designed to intercept flood flows from the catchments east of JEC and divert them through an outfall into the Red Sea, protecting the massive venture from flood damage.

The organization involved in undertaking the construction of this challenging initiative is Saudi Aramco Jazan Complex Projects Department (JCPD). The hydraulic design and structural design of JEC-FMC were carried out by AECOM. Construction of

Unit Conversions

- Admixture dosage: 1 L/m^3 = 0.2 gal./yd^3;
- Area: 1 km^2 = 0.39 mile^2;
- Density: 1 kg/m^3 = 1.7 lb/yd^3;
- Length: 1 km = 0.62 mile, 1 m = 3.3 ft, 1 mm = 0.04 in.;
- Mass: 1 tonne = 1.1 ton;
- Modulus of subgrade reaction: 1 kN/m^3 = 0.004 lbf/in.^{3};
- Pressure: 1 MPa = 145 psi;
- Soil bearing capacity: 1 kN/m^2 = 21 lbf/ft^2;
- Speed: 1 m/s = 3.3 ft/s;
- Temperature: °F = 1.8 × °C + 32; and
- Volume: 1 m^3 = 1.3 yd^3.

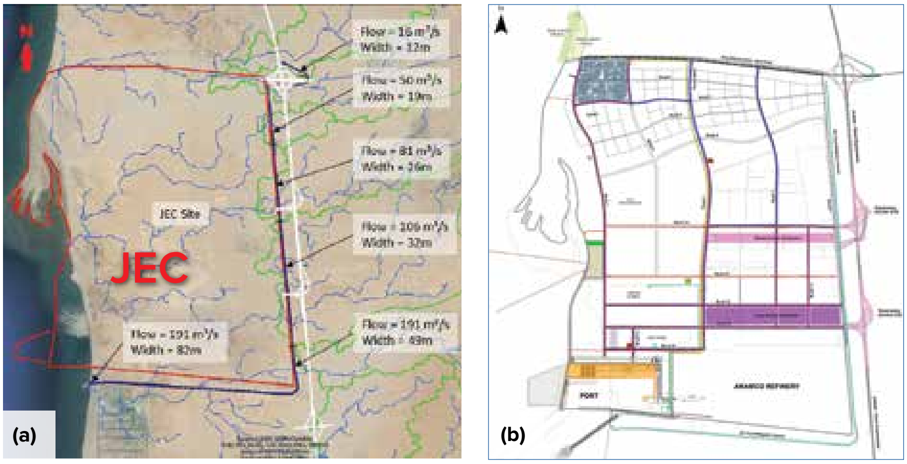


Fig. 2: JEC flood mitigation channel: (a) cumulative design flows and required widths; and (b) the channel passes the Aramco Refinery, located at the southeast corner of the site

the channel was carried out by a single contractor, Al-Yamama Company for Trading and Contracting (AYC). Design supervision was carried out by Saudi Aramco Consulting Services Department (CSD). A comprehensive research scope, including the monitoring of selected research segments in JEC-FMC, was carried out by King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia.

The Channel

The JEC-FMC is designed to prevent flooding of the low-lying JEC industries caused by floodwaters originating from the catchments on the eastern plain of the city and the catchment of the Baish Dam further east. The floodwaters will be intercepted at the eastern boundary of JEC and diverted into the Red Sea through the channel. The JEC-FMC originates from the upper northeastern point of the city and runs south, parallel to the eastern boundary of JEC, before turning west on the southern edge of the city and running along the southern boundary into the Red Sea (Fig. 2). It protects the residential and industrial areas and the major Aramco Refinery, discharging the floodwater into the sea adjacent to the industrial port (Fig. 2).

For hydraulic performance and optimal land use, a concrete lining was the most viable option for the JEC-FMC. Catering to the accumulating floodwaters along the length of the channel, the cross section of the channel increases incrementally from the upstream end to the outfall. The depth of the channel is kept constant (2 m) over the entire length of the channel.

Hydraulic and Structural Design

The channel was designed using Eurocodes (EN standards), pre-EN standards revisions of the British Standards (BS), and other design standards and manuals.[1-13] The channel geometry was developed based on catchment models and a 39% probability of a 100-year return period flooding event occurring during the 50-year service life of the channel.

The trapezoidal channel was designed to carry the accumulating design flows shown in Fig. 2(a). The figure also shows the required top widths per the hydraulic design, with the channel divided into six segments. Channel side slopes were set at a gradient of 1:2 (V:H) to meet the hydraulic requirements. The longitudinal gradient of the channel was set at 1 in 900 to 1000 to maintain a subcritical flow regime with maximum velocity limited to 4.6 m/s. Because the natural slope is steeper than the channel gradient, steps were provided along the length of the channel with 200 or 1000 mm drops in the invert level. Table 1 lists geometric details and the design velocity in the JEC-FMC segments. The width of the channel at the base gradually increases from 4 to 74 m by increases in width at five locations, together with a transition length varying from 6 to 29 m. The outfall structure is a 300 m long trapezoidal channel, with the width varying from 49 to 82 m. The depth of the channel was maintained at a constant 2 m across the length of the channel. For the maintenance of the channel, a 5 m wide access ramp was provided at selected locations along the length.

In the original design, the thickness of the base slab was determined to be 200 mm based on the following design and operation criteria:

- The channel is fully loaded with a 2 m water column;
- The maintenance vehicle is a five-axle truck with 10.5 tonne (23 kip) axle loads as per Reference 14;
- The soil investigation in the adjacent areas indicated that the soil is a cohesionless soil with angle of internal friction ranging from 30 to 34 degrees and a modulus of subgrade reaction of 30,000 kN/m^3;
- A maximum California Bearing Ratio (CBR) value of 10% for the formation, including the drainage layer;
- An assumption that 2.54 million standard traffic axles may be applied over the 50-year design life of the structure; and

Table 1:

Channel segments, geometry, and hydraulic design parameters. At all sections, the channel geometry is trapezoidal with 1:2 side slopes and 2 m minimum depth

Channel segment	Design flow, m^3/s	Length, m	Bed width, m	Top width, m	Design depth, m	Design freeboard, m	Design velocity, m/s
JEC_FLD0	16	1200	4	12	1.55	0.45	1.49
JEC_FLD1	50	2200	11	19	1.55	0.45	2.37
JEC_FLD2	81	2960	18	26	1.55	0.45	2.52
JEC_FLD3	106	4850	24	32	1.55	0.45	2.66
JEC_FLD4	191	9960	41	49	1.55	0.45	2.82
JEC_FLD5	191	300	74	82	1.10	0.90	2.31

Note: 1 m^3/s = 264 gal./s; 1 m = 3.3 ft; 1 m/s = 3.3 ft/s

- Thermal and shrinkage crack width limited to 0.3 mm per BS 8007.[8]

A typical section of the channel is shown in Fig. 3. A 1 m wide berm and a 1 m deep downstand beam were included at the end of each of the sloped sides to prevent scouring at the back. Guard rails were provided on the two edges of the channel, with a 4 m wide road constructed for access and maintenance of the channel.

The groundwater table along the alignment of the channel ranges from 3 to 10 m below the natural ground level. Weep holes were therefore included in the design to preclude upward thrust force on the concrete lining and dissipate the groundwater pressure if the water table rises.

The cross section of the JEC-FMC includes:

- Excavated/backfilled and compacted ground;
- A filter fabric over the compacted ground;
- A 200 mm granular drainage layer placed on the filter fabric for dissipation of groundwater pressure;
- A 50 mm thick, lean concrete blinding layer over the drainage layer; and
- A 200 mm thick concrete lining.

The weep holes in the base slab comprise 160 mm diameter PVC pipe sections extending from the drainage layer through the concrete lining. They were installed in a 4 x 4 m pattern in the base slab. Also, a line of horizontal weep holes, also comprised of 160 mm diameter PVC pipe, was installed in the channel sides 200 mm above the base slab and spaced at 4 m centers along the length of the channel.

In the initial design, the reinforcement for the concrete lining comprised 12 mm diameter steel reinforcing bars spaced at 150 mm centers in both directions. A top clear cover of 75 mm was required for the bars. The design also called for partial contraction joints at 7.5 m on center and expansion joints at 30 m on center in both the transverse and the longitudinal directions. The original design also called for the lining thickness to taper to 175 mm on the side slopes.

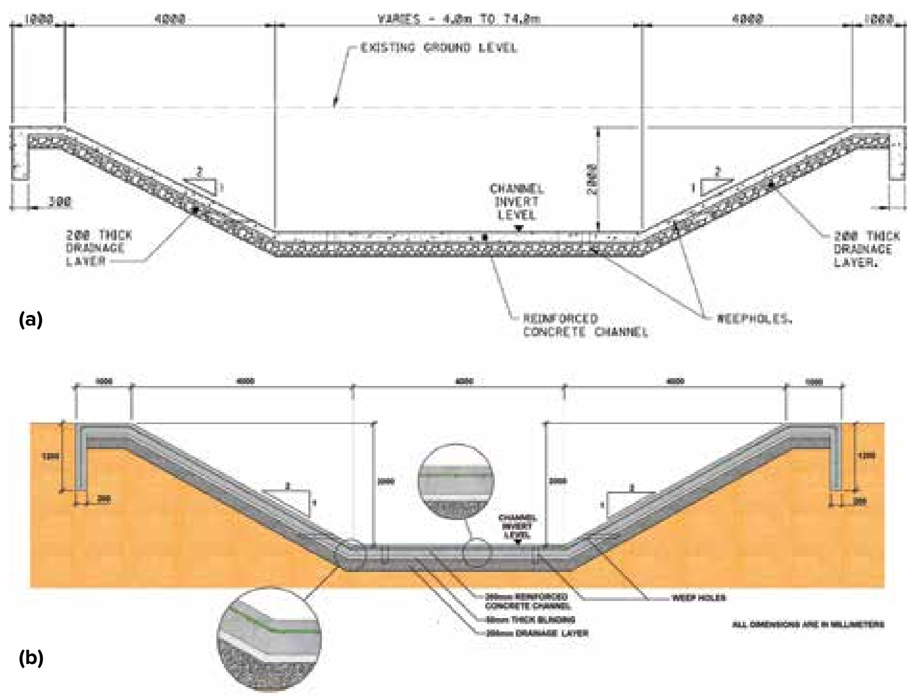


Fig 3: The flood mitigation channel: (a) cross section showing the original design with epoxy-coated steel (ECS) bars; and (b) cross section at the upstream end, showing the revised design with GFRP bars (Note: 1 m = 3.3 ft; 1 mm = 0.04 in.)

Durability Aspects of the Original Design with Steel Bars

The original goal for the channel was a design life of 50 years, during which minor maintenance would be needed, and no major repair work should be undertaken. The channel in the north-south and east-west directions (Fig. 2) traverses through an undulating terrain, gently falling toward the south and subsequently to the west up to the outfall. Salt-laden marshes, flats, and sand dunes characterize the pathway of the flood mitigation channel. The harsh ambient environmental conditions in JEC, subsoil chlorides and sulfates (at concentrations in the soil of about 1.6% and 0.5%, respectively), widespread sandstorms, and the salt-contaminated floodwater rolling through the deserts into the channel can expose the channel to an extreme environment. Because this could lead to corrosion of reinforcing steel several years ahead of the design life, the project team decided to reinforce the channel concrete with epoxy-coated steel (ECS) bars. To minimize the risk of sulfate attack, the concrete mixture was designed to comprise 345 kg/m^3 Type V portland cement and 25 kg/m^3 silica fume. The crack width was predicted based on Reference 10, with the assumption of 32°C placement temperature and 60°C peak hydration temperature (without inclusion of solar gain during the hydration). The temperature change values for the calculations were determined based on maximum and minimum average temperatures in Jazan city, and the calculations included the effect of reduced bond strength of the ECS bars.

Switching to GFRP Reinforcement

Saudi Aramco has many reinforced concrete structures and other concrete infrastructure in a host of industrial facilities for oil and gas production and processing. These facilities are mostly located on the coastline of the Red Sea and the Arabian Gulf of the country and in desert areas in the eastern region. Due to the prevailing harsh environment, corrosion of steel reinforcement can take place at a rapid pace, leading to cracking, delamination, and spalling of concrete cover, eventually causing substantial loss of the total steel section.

In January 2018, Saudi Aramco made the strategic decision to use nonmetallic reinforcement in concrete structures in company facilities. In line with this vision, a major decision was taken to transform the JEC-FMC from a structure reinforced with ECS bars to a structure reinforced with GFRP bars. As a result, the project is now expected to provide a maintenance-free service life exceeding 100 years.

GFRP is a composite, normally comprising vinyl ester resin and E-CR glass fibers. The use of GFRP bars as a concrete reinforcement has gained popularity in recent years, as designers have gained confidence in the material and advances in manufacturing processes and increased competition have made it more cost-competitive with conventional reinforcing steel. In addition to corrosion resistance, GFRP bars offer a high strength-weight ratio, electromagnetic neutrality, and high fatigue endurance. Further, the low weight of bars reduces costs for transportation and installation. While thermal expansion and stiffness compatibility with concrete are quite good, GFRP bars have a relatively low elastic modulus, shear strength, and tensile creep rupture stress. The latter factors are not major considerations for ground-supported slabs such as the FMC.

After the pertinent redesign, discussion, and securing an accord with the project contractor, the transformation from ECS bars to GFRP bars culminated in a contract amendment in December 2018. Three international GFRP bar vendors were approved based on their product quality, technical capabilities, and localization plan. The vendors and important properties of the supplied bars are listed in Table 2. Although half of the reinforcing for the JEC-FMC project was not produced locally, a localization criterion in the selection of vendors has been deemed highly important for future work, as local production will minimize delivery time, reduce material and transportation costs, and enhance the industrial base in the Kingdom.

Design

The codes and standards used in the project included References 15 through 28. The alignment and geometric design of the JEC-FMC were retained as per the original design. The main criteria considered for the design with GFRP reinforcement included:

- Crack width limited to 0.7 mm as per ACI 440.1R-15[16] (AASHTO LRFD GFRP Guide Specification[17] allows < 1 mm);
- Crack spacing restricted to between 0.9 and 2.4 m; and

Table 2:
Properties of the GFRP bars as provided by three manufacturers

Manufacturer, production base	Portion of total quantity of GFRP bars, %	Nominal bar diameter, mm	ASTM bar No.	Nominal cross-sectional area, mm^2	Guaranteed/ measured ultimate tensile strength, MPa	Ultimate tensile strain, %	Modulus of elasticity, GPa
Pultron, Dubai	50	14	—	149	850 / >900	1.6	52
Galen, Russia	25	12.45	4	121.7	1065 / 1223	2.4	50.1
Dextra, China	25	12.7	4	127	900	1.8	50

Note: 1 mm = 0.04 in.; 1 mm^2 = 0.0016 in.^{2}; 1 MPa = 145 psi; 1 GPa = 145 ksi

- Limiting tensile stress in GFRP bars to 30 to 40% of the guaranteed tensile strength.

The design of the GFRP-reinforced concrete structure for JEC-FMC was carried out as per ACI 440.1R-15. The thickness of both the base slab and side slopes was kept at 200 mm to allow greater uniformity during construction. Early thermal cracking was based on a casting temperature of 25°C and a relative humidity of 55%. As per Section 7.3.1 of ACI 440.1R-15, the maximum crack width was based on aesthetics—the harsh environment has no impact on the GFRP bars, and the GFRP-reinforced concrete can tolerate higher crack widths and lower cover. For crack control, the design called for the GFRP bars to be placed in the top one-third of the slab, so the 75 mm top cover was maintained from the original design. Due to the change in the crack width limitations from 0.3 mm in the original design to 0.7 mm, the spacing of the GFRP bars was changed from 150 mm on center. The final design included M13 (No. 4) GFRP bars spaced at 200 mm on center in both the longitudinal and the transverse directions.

As per ASTM D7957/7957M,[24] M13 GFRP bars have a nominal diameter of 13.7 mm. A minimum guaranteed tensile strength of 600 MPa was considered, with an environmental factor C_E of 0.7. The guaranteed modulus of elasticity of the GFRP bars was 50 GPa. A soil-bearing capacity of 125 kN/m^2 and a modulus of subgrade reaction of 30,000 kN/m^3 were considered for the design of the slab.

A typical section of the GFRP-reinforced JEC-FMC at the upstream end as well as the original design with ECS bars are shown in Fig. 3. The section includes a filter fabric placed on top of the excavated/backfilled and compacted soil, a 200 mm thick granular drainage layer placed on top of the fabric for dissipation of groundwater pressure, and a 50 mm thick blinding concrete layer. The GFRP bars were placed on plastic pipe chairs over the blinding layer. Weep holes were created using 160 mm diameter pipes spaced at 4 m centers in both longitudinal and transverse directions. Finally, a 200 mm thick concrete lining was placed on the blinding layer.

Concrete Grade C25 (25 MPa compressive strength at 28 days) was recommended as per the design details for the GFRP-reinforced channel with a cement content of 320 kg/m^3. The microsilica specified for the ECS bar design was withdrawn, and the cement content was reduced by 50 kg/m^3 due to the larger tolerance in crack width and the fact that the GFRP bars will not corrode.

Based on thermal cracking computations, the spacing of the contraction joints in the base slab was changed from 7.5 m on center to 6 m on center in each direction. The contraction joints were designed to be 10 mm wide and 50 mm deep.

Based on thermal loading, expansion joints were provided in both longitudinal and transverse directions at 30 m on center. A schematic of a transverse expansion joint is shown in Fig. 4. The joint is 25 mm wide and 200 mm deep. Stainless steel dowel bars, 900 mm long and spaced at 250 mm, were used to transfer shear at the expansion joints. In one segment, the dowel bar is bonded to the concrete. In the downstream segment, it is allowed to move freely within a plastic pipe sleeve. The stainless-steel bars were already procured for the project as per the original design, so no consideration was given for a change to GFRP bars at the expansion joints. The lap length was kept at 750 mm with a clear cover of 75 mm.

Construction

Construction of the JEC-FMC commenced with a major excavation along the alignment of the channel followed by roller compaction of the subgrade. About 6.2 × 10^6 m^3 of earth was excavated before placement of the geotextile fabric and the 200 mm thick drainage layer. Figure 5 shows the placement of the drainage layer and the lean concrete blinding

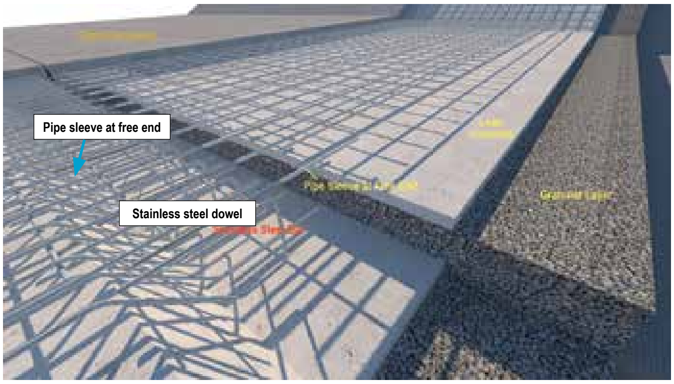


Fig. 4: Computer rendering of a typical transverse expansion joint

Fig. 5: Placement of the drainage layer: (a) for the base slab; and (b) for the sloped sides. The drainage layer for each of the sloped sides of the channel was placed after completion of the blinding layer for the base

layer. Figure 6 shows the storage and placement of the GFRP bars for a typical 30 x 30 m panel of the base slab. A crew of eight worked on each of the panels to tie the GFRP bars into a grid and construct the formwork for the base slab and side slab. Figure 7 shows the splice bars that were used to tie the sloped sides of the channel to the base slab; a segment in which the GFRP bars have been placed over the entire channel section, ready for concrete placement; and a detailed view of the lap splices at the slope-base junction as well as weep holes and bar supports (PVC pipe sections).

The concrete mixture comprised:

- 371 kg/m^3 of Type V cement;
- 1136 kg/m^3 of 19 mm (3/4 in.) maximum size aggregate;
- 773 kg/m^3 of fine aggregate;
- 116 kg/m^3 of water, resulting in a water-cement ratio of 0.40; and

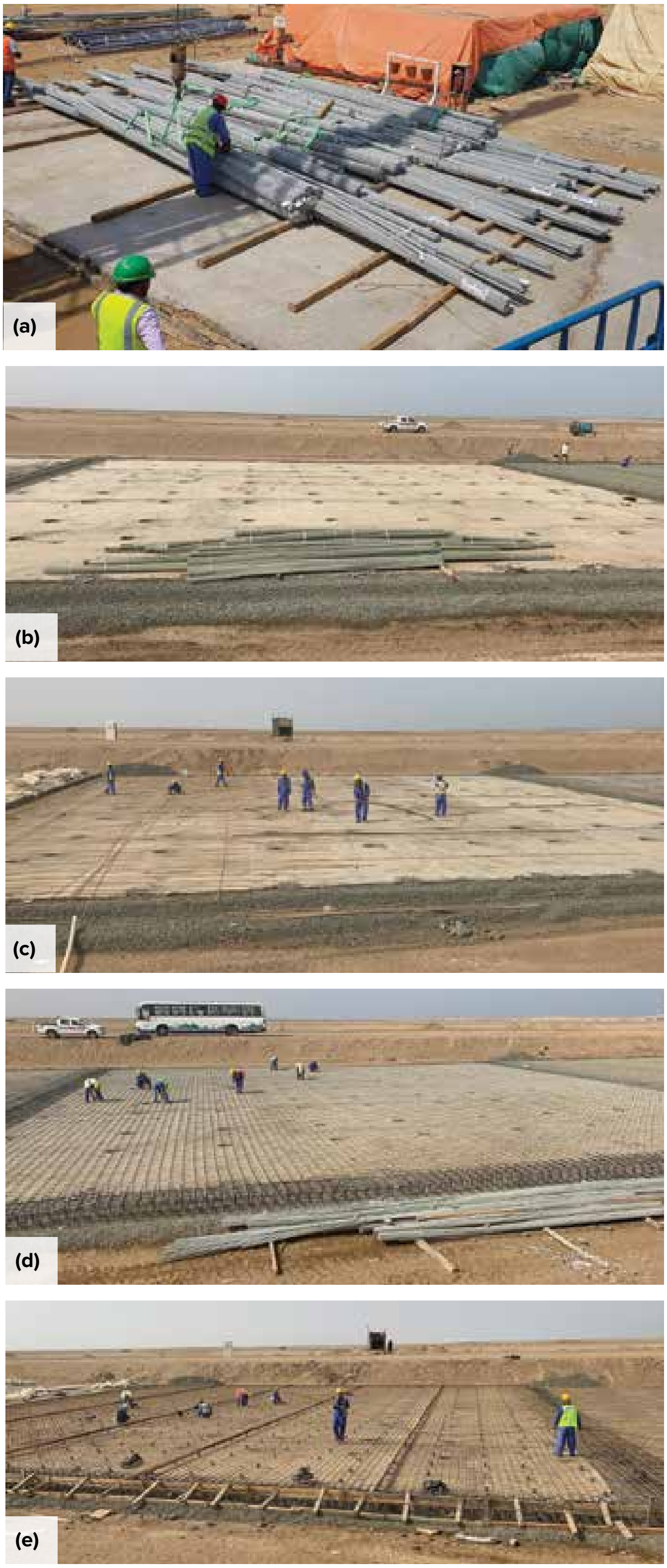


Fig. 6: The base slab was reinforced with grids of GFRP bars: (a) delivery of bars; (b) storage of bars on the blinding layer of an interior panel of the base slab (note openings in the blinding layer for later installation of weep hole pipes); (c) initial placement of bars; (d) grid assembly; and (e) final preparation of bar grid and longitudinal joint formwork

Fig. 7: The sloped sides of the JEC-FMC were tied to the base slab using bespoke splice bars: (a) a worker carries a bundle of splice bars; (b) prior to concrete placement, an overview of an upstream section of the JEC-FMC, showing grids, weep holes, and channel edge formwork; and (c) detail of lap splice at base-slope intersection

- 6.0 L/m^3 of high-range water-reducing admixture.

The concrete lining was placed in 6 m wide by 30 m long panels, in staggered placements as shown in Fig. 8. Two concrete batching plants were established at the site for the continuous supply of concrete.

Cost Aspects

After almost 3 years of project execution, Saudi Aramco and the contractor, AYC, jointly investigated the costs, advantages, and disadvantages of completing the project using GFRP bars in lieu of ECS bars. The study was based on a typical 200 mm thick, 30 x 30 m panel (Fig. 6). We believe this assessment could be extended for similar large-scale projects, with concrete structure supported on grade under the Saudi Arabian conditions with respect to climate, materials, and labor costs.

In the original design, 12 mm diameter ECS bars were placed at 150 mm on center in both directions. A lap length of 600 mm was required, so the typical panel needed about 400 ECS bars totaling 12,480 m in length and 11.1 tonnes in weight. In the revised design, 13 mm diameter GFRP bars were placed at 200 mm on center in both directions. A lap length of 750 mm was required, so the typical panel needed about 300 GFRP bars totaling 9450 m in length and 3.1 tonnes in weight. The costs of the two options are summarized in Table 3. The following discussion provides the basis for the tabulated costs.

The contemporary market price of ECS cut and bent at site was \$0.74/m. The average market price of GFRP bars, including transportation, was also \$0.74/m. However, an additional 17% was required for customs and value-added taxes for the GFRP bars, as they were imported from Dubai, China, and Russia. These taxes raised the average price for GFRP bars to \$0.87/m. Once GFRP bar producers establish local plants, transportation and taxes will be reduced, making the GFRP option even more economical.

The original design called for a concrete mixture with 345 kg/m^3 Type V portland cement and 25 kg/m^3 silica fume, at about \$97/m^3 delivered and placed. The updated design called for 320 kg/m^3 of Type V cement, at about \$88/m^3 delivered and placed. Either option required 180 m^3 of concrete for a typical panel.

Other cost items included bar supports and bar ties. ECS bars are stiffer than GFRP bars, so fewer supports are needed. ECS bars required only 900 supports for the typical panel, while GFRP bars required 1125 supports per panel. A cost of \$0.54/unit was assumed. The ECS option required 20,400 bar ties per panel, while the GFRP option required 11,850 ties. A cost of \$0.14/tie was assumed.

Placement of the bars in a typical 30 x 30 x 0.2 m panel was expected to require 3 days for a team of 12 workers working on the ECS option and 1.5 days for a team of eight workers working on the GFRP option. Further, distribution of ECS reinforcement for the panel would require use of a crane during 2 of the 3 days of execution. Handling of the ECS bars

Fig. 8: Concrete placements at the JEC-FMC: (a) blinding layer in the sloped side; (b) a panel in the base slab; and (c) a panel at a sloped side

Table 3:
Cost comparison for ECS and GFRP options based on a 30 x 30 x 0.2 m slab panel

Expenditure item	ECS bars, $	GFRP bars, $	GFRP cost / ECS cost, %
Reinforcing bars	9235	8222	89
Concrete	17,514	15,840	90
Bar supports	486	608	125
Bar ties	2856	1659	58
Labor	3852	1284	33
Crane	1068	0	0
Safety gloves	9.60	15	156
Total	**35,021**	**27,628**	**79**

requires regular gloves with a cost of $0.80/pair, while handling of the GFRP bars requires leather gloves with a cost of $1.87/pair.

As Table 3 shows, the GFRP option resulted in a cost reduction of about 11% for reinforcing bars, 10% for concrete, 42% for bar ties, 100% for crane charges, and 67% for labor. The total direct cost savings for the GFRP bar option was therefore 21%. A life-cycle cost analysis (LCA) was not considered. We anticipate that for similar, large-scale projects, a significant reduction in cost could also be achieved with GFRP reinforcing bars.

Qualitative Aspects

The most relevant consideration when using GFRP bars is that they cannot be bent at site. The material must come already cut and bent from the manufacturer. This makes the system rigid and doesn't allow changes, adjustments, or replacement of damaged or missing bars. This also affects activities such as excavation, drainage layer, and blind concrete, which need to be executed with high accuracy, leaving low room for tolerance or errors. ECS bars are more flexible and adaptive under this point of view.

In terms of preservation, GFRP bars are not affected by chloride-bearing soil and water. However, GFRP bars are affected by ultraviolet radiation and should be covered if the exposure exceeds 3 months. The labor required for GFRP bar placements was significantly reduced compared with requirements to place conventional reinforcing bars, and no heavy equipment was needed for assembling the bars on the base slab and sloping sides of the channel. However, workers had to constrain the lightweight bars from floating during concrete placement.

Final Remarks

GFRP bars in concrete structures are now finding extensive acceptance as a major alternative to address the durability challenges in harsh conditions. The largest GFRP-bar reinforced concrete structure has been successfully completed for a major infrastructure project designed to protect the JEC in Saudi Arabia from flooding. About 10 million lineal m of GFRP bars have been used in the channel, along with about 188,000 m^3 of structural concrete and 45,000 m^3 of blinding concrete. The benefits accrued by switching from ECS bars to GFRP bars in the JEC-FMC include high durability and reduced project execution time.

After the successful completion of this project, many other projects in Saudi Aramco have adopted GFRP reinforcing bars in the construction of their concrete works. Saudi Aramco is collaborating with KFUPM and other research institutions to close the gap on some of the limitations of the GFRP bars and provide clarity on design criteria. Recently, Saudi Aramco and ACI announced the launch of NEx—a Center of Excellence for Nonmetallic Building Materials—to develop and promote the use of nonmetallic materials in the building and construction sector.

References

1. BS EN 1991-1-1:2002, "Eurocode 1: Actions on Structures—Part 1-1: General Actions - Densities, Self-weight, Imposed Loads for Buildings," European Committee for Standardization, Brussels, Belgium, 2002, 44 pp.

2. BS EN 1992-1-1:2004, "Eurocode 2: Design of Concrete Structures—Part 1-1: General Rules and Rules for Buildings," European Committee for Standardization, Brussels, Belgium, 2004, 225 pp.

3. BS EN 1997-1:2004, "Eurocode 7: Geotechnical Design—Part 1: General Rules," European Committee for Standardization, Brussels, Belgium, 2004, 168 pp.

4. BS 8002:1994, "Code of Practice for Earth Retaining Structures," British Standards Institution, London, UK, 1994, 144 pp.

5. BS 8004:2015, "Code of Practice for Foundations," British Standards Institution, London, UK, 2015, 112 pp.

6. BS 6031:2009, "Code of Practice for Earthworks," British Standards Institution, London, UK, 2009, 120 pp.

7. BS 8110-1:1997, "Structural Use of Concrete—Part 1: Code of Practice for Design and Construction," British Standards Institution, London, UK, 1997, 168 pp.

8. BS 8007:1987, "Code of Practice for Design of Concrete Structures for Retaining Aqueous Liquids," British Standards Institution, London, UK, 1987, 32 pp.

9. CIRIA C683, "The Rock Manual. The Use of Rock in Hydraulic Engineering," second edition, CIRIA, London, UK, 2007, 35 pp.

10. Bamforth, P.B., CIRIA C660, "Early-Age Thermal Crack Control in Concrete," CIRIA, London, UK, 2007, 23 pp.

11. Balkham, M.; Fosbeary, C.; Kitchen, A.; and Rickard, C., CIRIA C689, "Culvert Design and Operation Guide," CIRIA, London, UK, 2010, 50 pp.

12. "Design Standard No. 14: Appurtenant Structures for Dams (Spillways and Outlet Works) Design Standards," Chapter 3: General Spillway Design Considerations, U.S. Department of Interior Bureau of Reclamation, Washington, DC, 2014, 253 pp.

13. "Jeddah Storm Water Drainage Manual," Saudi Aramco, Jazan, Saudi Arabia, 2014, 232 pp.

14. Hassan, K.E.; Chandler, J.W.E.; Harding, H.M.; and Dudgeon, R.P., "New Continuously Reinforced Concrete Pavement Designs," Report TRL630, Transport Research Laboratory, Berkshire, UK, 2005, 36 pp.

15. ASTM C150/C150M-20, "Standard Specification for Portland Cement," ASTM International, West Conshohocken, PA, 2020, 9 pp.

16. ACI Committee 440, "Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars (ACI 440.1R-15)," American Concrete Institute, Farmington Hills, MI, 88 pp.

17. "AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings," first edition, AASHTO, Washington, DC, 2009, 68 pp.

18. "AASHTO LRFD Bridge Design Specifications," eighth edition, AASHTO, Washington, DC, 2017, 438 pp.

19. "Technical Report No. 66: External In-Situ Concrete Paving," Concrete Society, Camberley, UK, 2007, 83 pp.

20. "*fib* Bulletin No. 40: FRP Reinforcement in RC Structures," *fib*, Lausanne, Switzerland, 2007, 160 pp.

21. ACI Committee 318, "Building Code Requirements for Structural

Concrete (ACI 318-14) and Commentary (ACI 318R-14)," American Concrete Institute, Farmington Hills, MI, 2014, 519 pp.

22. 12-SAMSS-027, "Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement," Materials System Specification, Saudi Aramco, Jazan, Saudi Arabia, 2017, 8 pp.

23. SAES-Q-001, "Criteria for Design and Construction of Concrete Structures," Saudi Aramco, Jazan, Saudi Arabia, 2016, 24 pp.

24. ASTM D7957/D7957M-17, "Standards Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement," ASTM International, West Conshohocken, PA, 2017, 5 pp.

25. "AASHTO Guide for Design of Pavement Structures," AASHTO, Washington, DC, 1993, 640 pp.

26. DMRB 7.2.1, "HD 24/06: Pavement Design and Maintenance. Pavement Design and Construction. Traffic Assessment," Highways England, London, UK, 2006, 20 pp.

27. ACI Committee 440, "Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars (ACI 440.5-08)," American Concrete Institute, Farmington Hills, MI, 2008, 5 pp.

28. ACI Committee 440, "Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement (ACI 440.6-08) (Reapproved 2017)," American Concrete Institute, Farmington Hills, MI, 2008, 6 pp.

Selected for reader interest by the editors.

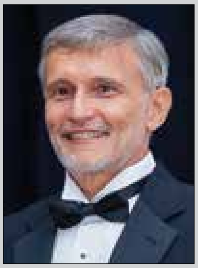
Eduardo A. Villen Salan has been involved in the execution of infrastructure projects for the last 20-plus years, including bridges, high-speed railways, tunnels, highways, water treatment plants, pipelines, channels, refineries, and buildings. A project management professional and professional engineer, he serves as a member of the Saudi Aramco project management team assigned to the Jazan Complex Projects Department. He received his master's degree in civil engineering.

Muhammad K. Rahman is a Researcher and faculty member at the Center for Building and Construction Research Institute at King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia, and is Vice President of the ACI Saudi Arabia Chapter. He received his PhD in structural engineering and has conducted several major Saudi Aramco and other client-funded research projects as principal investigator. His current research focus is on nonmetallic reinforcement in concrete.

Sami Al-Ghamdi is the Chief Technology Officer at Novel Nonmetallic Manufacturing Solutions, a joint venture between Saudi Aramco and Baker Hughes. In his 21 years of experience at Saudi Aramco, he has worked on the design, consulting, and project management of large-scale industrial and infrastructure projects. His experience also includes the assessment and rehabilitation of existing structures. He is the Chairman of the civil standards committee for Saudi Aramco and a member of ISO/TC 71, Concrete, Reinforced Concrete and Pre-stressed Concrete.

Jihad Sakr is a Senior Project Manager at Al-Yamama Company for Trading & Contracting, Jazan, Saudi Arabia. He has over 25 years of experience in execution of projects and is adept in ensuring compliance with Saudi Aramco procedural, engineering, and construction guidelines. He specializes in assessing project needs while adhering to cost-effective quality control standards. He received his master's degree in construction management and a BSc in civil engineering.

Mesfer M. Al-Zahrani is a Vice President for Academic Affairs and a faculty member in the Civil Engineering Department at KFUPM. For more than 30 years, he has conducted several studies and participated in funded projects as a principal investigator on the durability of construction materials, including concrete, composite materials, corrosion of steel reinforcement, and repair and rehabilitation of structures in marine environments.



Antonio Nanni, FACI, is an Inaugural Senior Scholar, Professor, and Chair of the Department of Civil, Architectural, and Environmental Engineering at the University of Miami, Miami, FL, USA. He is Chair of ACI Committee 549, Thin Reinforced Cementitious Products and Ferrocement, and a member of numerous ACI committees, including ACI Committee 440, Fiber-Reinforced Polymer Reinforcement. He has received several awards, including the 2014 IIFC Medal from the International Institute for FRP in Construction and the 2012 ASCE Henry L. Michel Award for Industry Advancement of Research.