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New directions for reinforced concrete coastal structures

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Abstract

Within the last century, coastal structures for infrastructure applications have traditionally been constructed with timber, structural steel, and/or steel-reinforced/prestressed concrete. Given asset owners' desires for increased service-life; reduced maintenance, repair and rehabilitation; liability; resilience; and sustainability, it has become clear that traditional construction materials cannot reliably meet these challenges without periodic and costly intervention. Fiber-Reinforced Polymer (FRP) composites have been successfully utilized for durable bridge applications for several decades, demonstrating their ability to provide reduced maintenance costs, extend service life, and significantly increase design durability. This paper explores a representative sample of these applications, related specifically to internal reinforcement for concrete structures in both passive (RC) and pre-tensioned (PC) applications, and contrasts them with the time-dependent effect and cost of corrosion in transportation infrastructure. Recent development of authoritative design guidelines within the US and international engineering communities is summarized and a examples of RC/PC verses FRP-RC/PC presented to show the sustainable (economic and environmental) advantage of composite structures in the coastal environment.

Keywords: Concrete bridges, Corrosion-resistant, Durability, Fiber-reinforced polymer, FRP

Introduction

Within the last century, coastal structures for infrastructure applications have traditionally been constructed with timber, structural steel, and/or steel-reinforced/prestressed concrete. Given public infrastructure owners' desire for increased service-life [1–3]; reduced maintenance, repair and rehabilitation liability [4, 5]; resilience [6]; and sustainability [7], it has become self-evident that traditional construction materials cannot reliably meet all these challenges for long-life coastal structures without periodic and often costly intervention ([8, 9] pp. 1–2). This observation is reinforced by the expanding gap between Operation and Maintenance expenditures, verses Capital investment for public infrastructure [10].

Traditional construction materials can provide improved service-life for reinforced concrete structures with appropriate combinations of supplemental materials, barrier coatings, stress reduction, and thicker concrete covers, but it is recognized that these structures will still require corrective repairs or replacement to reach contemporary service-life expectations (75 to 150 years) without compromising safety. Additionally, many mitigation techniques have been developed to delay or even reverse chloride ion ingress and steel depassivation through electro-chemical rehabilitation [11–14], and cathodic protection [15–18], but at significant relative expense and risk when contemplating the design of new coastal structures.

In the context of bridges, the corrosion of decks in North America is mostly due to the use of de-icing chemicals with collateral corrosion damage to beam ends and supporting pier caps due to runoff from leaking expansion joints, however the most prolific corrosion deterioration for bridge substructures is due to exposure to seawater in coastal structures, as recently reiterated by [19] (p.62): *"The most serious threat to bridges in Florida is the corrosion of steel reinforced concrete substructures in coastal regions"*. It is significant that this statement

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comes from a state transportation agency that has one of the lowest bridge deficiency ratings in the US at 2.1% [8], with the third highest state population and relatively young bridge inventory due to its rapidly growing population (and transportation infrastructure needs) since the 1950's.

An alternative and perhaps more rational solution for reinforced concrete is to drastically minimize or remove the risk of corrosion, by adopting either highly corrosion-resistant (HCR) or non-corrosive reinforcing materials, respectively. Fiber-Reinforced Polymers (FRP) are non-corrosive material options for both reinforced concrete (RC) and prestressed concrete (PC) that utilizes decades old technologies but have yet to be fully integrated into the structural materials selection process. High nickel and chromium content stainless-steel (316 and 2205 alloys) are examples of HCR reinforcing materials that are gaining increased use for both new and rehabilitated structures. Aramid, basalt, carbon, and glass are example structural fibers that have been successfully utilized and increasing codified ([20–24]; ASTM 7957–17 [25];; CSA 806–19 [26–28];) for both RC and PC structural applications [29]. This paper focuses on the successful applications of FRP-RC & PC, representing both structurally and economically reliable solutions.

The inevitability of corrosion in coastal structures with traditional materials

The time-dependent effect and cost of corrosion in transportation infrastructure is of extreme concern to owners of structures near the coastline. Repairs due to corrosion of reinforcing steel in concrete is estimated to be the most expensive repairs performed on coastal structures [19, 30, 31]. Chlorides accumulate on the concrete surface either through direct contact with the surrounding waterbody, by contaminated runoff flowing over the surface, or by exposure to salt-laden airborne spray. The presence and accumulation of chlorides at the surface drives ingress under a combination of complex transport processes, including absorption, convection, diffusion, migration, permeation, and thermodiffusion [32]. The chloride ingress process is further complicated by chloride binding, ionic interaction, aging factors, temperature, humidity, and submerged pressure effects [33–35]. Subsequent durability modelling is complicated by the presence of cracks in the concrete, the relative sustained or fatigue stress in the internal reinforcing, and reinforcing alloy and microstructure [36–38].

Under optimal conditions, the reinforcement in concrete remains in a passivated state stabilized by the high alkalinity of the concrete. However, when the chloride concentration exceeds a critical threshold at the reinforcement level, the passivation film is destabilized, and the initiation of localized corrosion occurs. Furthermore, the process of carbonation reduces the concrete alkalinity and hinders passivation, accelerating corrosion in the presence of chlorides [39, 40]. Carbonation generally fosters corrosion over a larger surface of the reinforcement, whereas chloride induced corrosion can be very localized for high performance concrete, especially in the presence of cracks [41]. Recent studies on the coupling of carbonation and chloride induced corrosion has shown accelerated effects.

Corrosion degrades the reinforcement resulting in section loss and/or debonding with the surrounding concrete. The corrosion is further aggravated due to the formation of expansive oxidation products, producing cracks and splitting of the concrete to the surface, which then accelerates the access of chlorides. This increased chloride access eventually leads to delamination of the concrete cover and further loss of structural integrity. Chloride diffusion is accelerated, and corrosion initiation is more likely under carbonation than under only chloride ingress, likely in part due to carbonation releasing a certain portion of the bound chlorides into the pore solution (Zhu et al. [42, 43]). Much experimental work on chloride penetration and corrosion under a variety of conditions has been carried out, and, more recently, modeling approaches, including through artificial neural networks have shed light on this topic [44].

Several mitigation techniques including: 1) less permeable concrete formulations, primarily using supplemental pozzolans (e.g. granulated blast furnace slag, flyash, silica fume, metakaoline); 2) increased concrete cover; 3) topical or barrier treatments to seal the concrete surface (e.g. silanes, methyl methacrylate), are all recognized and currently used to reduce the penetration of chlorides in the concrete. However, these mitigation strategies only delay the onset of corrosion. Eventually, the chloride ions penetrate the cover concrete and accumulate to the critical concentration threshold which initiates corrosion of the internal steel rebars. Effective cathodic protection can be installed to delay or even prevent chloride ingress, but at additional expense, maintenance, and periodic replacement. Consideration of concrete cracking in corrosion durability models such as [45], *fib* Bulletin 34 [46], and [47], have been limited but recent research [48] highlights the accelerating effect, confirming anecdotal and documented observations of concrete structures in aggressive environments as identified by [19] p.62).

Quantifying the corrosion liability of highway bridges & structures

The total annual cost of corrosion in the United State was reported as $276 billion in 2002. In the world's second largest economy (China), the annual cost of corrosion was similarly estimated at $310 billion [49]. It was further estimated that the annual direct cost for maintenance for concrete bridge decks due to corrosion of the reinforcement in the United States is around $2 billion, and another $2 billion spent for maintenance on concrete substructures due to the same reason [50]. Although the US national estimates are almost two decades old, the situation has not improved, with now almost 40% of US bridges over 50-years old [8], which was the typical design life expectation at the time of design. On a broader perspective, the 2016 IMPACT report [51] for similar applications, estimates a return on investment of 13 times expenditure for *"corrosion prevention of rebar in concrete in critical facilities located in coastal environments"*.

Response to an ever-growing challenge

Current Federal Highway Administration (FHWA) and American Association of State Highway and Transportation Officials (AASHTO) funded efforts are primarily focused on preservation and quantification of the existing inventory of bridges to generate better predictive models and longer service life. The 2015 Fixing America's Surface Transportation (FAST) Act required that each State transportation agency develop a risk-based Transportation Asset Management Plan for all pavements and bridges on the National Highway System. The need to focus on asset preservation through proactive and targeted maintenance, repair, and rehabilitation (MR&R) is indicatively reflected across other US public infrastructure sectors in a recent Congressional Budget Office report [10]. The graph in Fig. 1 was extracted from this report and shows a broadening gap between Operation and Maintenance costs verses Capital expenditure.

Given that for highway structures and bridges the operational costs are generally minimal, except for moveable bridges, most of this relative cost escalation can be attributed to an increasing maintenance burden. Whether the cost escalations are due to reactive or proactive maintenance, and what percentage can be attributed to the growing inventory size, is of little consequence to the focus and need identified in this paper for reducing the MR&R burden. This strategy is also in direct alignment with the shared goal of the "ASCE Grand Challenge" to reduce infrastructure lifecycle costs by 50% by 2025 [4].

A leading example of this strategy is the Long-Term Bridge Performance (LTBP) program [5]. Some of the goals of the LTBP program to quantify and predictively model durability performance are poignantly relevant to this paper, including:

- Advance research in deterioration and predictive models.
- Apply cost analysis effectively.
- Support development of improved design methods and maintenance/bridge preservation practices.
- Quantify the effectiveness of various maintenance, repair, and rehabilitation strategies.

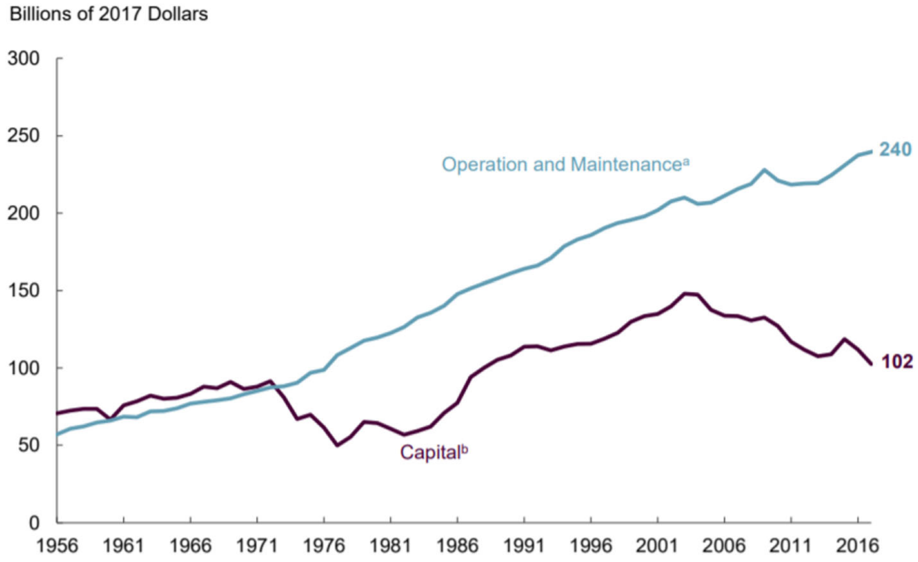

Fig. 1 State and Local Spending on Transportation and Water Infrastructure, by Category of Spending, 1956 to 2017 [10] p.16. **a** Dollar amounts are adjusted to remove the effects of inflation using price indexes for government spending that measure the prices of goods and services consumed by governments, including materials and other inputs used to operate and maintain transportation and water infrastructure. **b** Dollar amounts are adjusted to remove the effects of inflation using price indexes for government spending that measure the prices of materials and other inputs used to build transportation and water infrastructure

This federal prioritization is understandable given accelerating replacement needs as "Interstate Era" bridges begin to collectively age well beyond their originally envisioned service-life. Without the injection of a major capitol works program, replacement of the deteriorating inventory is currently not possible with existing funding levels and revenue generation mechanisms.

There has been specific focus in the last decade on improving bridge construction durability through several FHWA "Every Day Counts" (EDC) program initiatives, including: Prefabricated Bridge Elements and Systems (PBES) [52]; Accelerated Bridge Construction [53]; Ultra-High Performance Concrete for Precast Connections [54]; and Ultra-High Performance Concrete for PBES [55]. Each of these EDC initiatives had goals beyond just accelerating construction and the associated safety and congestion reduction benefits, by intending to also improve durability through industrialized quality-controlled manufacturing of components and creating robust connection systems with reduced maintenance. Concrete cover thickness is sometimes allowed to be reduced under PBES, and AASHTO has allowed such practice for precast culvert structural elements for many years under their LRFD bridge design specifications, so consequently the additional quality of manufacturing may not always lead to increased durability, but only maintain the existing deemed-to-comply specification performance requirements.

Under-utilized material technology and new tools

While all these programs have primarily focused on improving quality and speed of construction, the class of durable Fiber-Reinforced Polymer (FRP) reinforcing has remained largely underutilized since the expiration of the Innovative Bridge Research and Construction (IBRC) funding program in 2005 [56]. This delayed attention to FRP is likely to change with FHWA's establishment of several regional University Transportation Centers (UTC) with their research priority of "Improving Durability and Extending the Life of Transportation Infrastructure" [57–60], and more recently, establishment of the National Center for Transportation Infrastructure Durability and Life-Extension UTC [61]. With a focus on durability and resilience, these UTCs hold strong promise through their collaboration efforts, for identifying scalable solutions that can economically extend the service life of our transportation infrastructure. Most recently, FHWA launched a new FRP Composites Technology website in April 2020 [62].

Recent development of authoritative design guidelines for both FRP-RC and FRP-PC in the US [26, 27] and Canada [28] complement and advance the existing repository of international design guidance [20–25].

Additionally, the second joint Strategic Highway Research Program [63] from 2007 to 2019, established a good foundation for future development of a Service-Life Design bridge specification, recognizing the importance of durability in the holistic cost of transportation infrastructure. Although FRP was not explicitly considered in the development of the final "Guide Specification for the Service Life Design of Highway Bridges" [1], a framework has been established that could also integrate FRP structural materials under "Class D" reinforcement (highly corrosion-resistant materials).

Drastic consequences demand different solutions

There is little dispute regarding the need for corrosion mitigation solutions for existing structures while simultaneously researching improved solutions for new construction. However, there is a missed opportunity with existing FRP technology that could be broadly deployed immediately. There will likely never be sufficient funding to replace all the deficient infrastructure with new durable, resilient solutions. However, for those replacements that are feasible, it is considered by the authors a societal disservice to continue building strategic infrastructure using conventional legacy materials with proven inability to weather the challenge of highly corrosive environments. The most rational solution is to eliminate the possibilities of corrosion completely rather than delay it.

There has also been an underutilization of life-cycle cost (LCC) analysis for bridges and seawall structures in comparing the true cost of ownership. When LCC is utilized, the durability models are typically optimistic and biased against more expensive durable solution by: 1) ignoring the effects of cracking in concrete as previously discussed; 2) use of inflated discount rates (3 to 6%) not reflective of public infrastructure investment; and 3) lack of recognition that the construction cost inflation index [64] is significantly higher than general inflation which is implicitly incorporated into published real discount rates such as [65]. In recent years OMB Circular No. A-94 Appendix C has published much lower recommended discount rates but these still suffer from the limitations identified above when applied to 75 or 100 year target service life.

FRP composites have been successfully utilized for durable reinforced and prestressed concrete bridge applications for more than 30 years, demonstrating their ability to provide reduced maintenance cost and extended service-life, due to significantly increased durability. The FHWA EDC and LTBP programs could significantly benefit from embracing FRP-RC/PC technologies for Highly Corrosion-Resistant (HCR-) solutions and thereby substantially improve the life-cycle cost and future asset management of owners' bridge inventories.

Initial higher cost is often cited by owners and engineers for not specifying FRP composites in more applications, however these low usage volumes continue to contribute to higher cost thru a lack of industrial scaling and competition. Furthermore, a lack of demand from owners and engineers for higher mechanical performance properties and refinement of reliability margins of safety consistent with conventional materials, ensures that less competitive designs propagate.

A collaborative proposal from composites industry representatives, Transportation Research Board Committee AFF80, and AASHTO subcommittee T-6 (FRP Composites), under the EDC-5 solicitation process was unsuccessful in 2018 [66]. Some of the collective concerns from reviewers included: *"How do we inspect, load rate, maintain, repair, and confidently determine remaining service life"*, for these types of bridge structures or components? Many of these concerns may be resolved under future research, such as the recent FHWA Broad Agency Announcement 693JJ321BAA0001, Topic 10: HIBS10-FRP-001 (Safety Inspection and Evaluation of Bridges with FRP Composites). While these are important questions to be more fully researched and refined, 30-years of experience from existing FRP-RC/PC infrastructure and the lack of comprehensive cost-effective solutions with conventional materials, should be sufficient motivation to proceed with broader adoption as Florida Department of Transportation (FDOT) and a few other leading state transportation agencies are doing [67].

Structure type and components most benefiting from FRPRC-solutions

Composition

FRP reinforcement is made from continuous fibers, typically glass (GFRP), basalt (BFRP), carbon (CFRP), or aramid (AFRP). Fibers are impregnated with polymeric resin, typically thermoset vinyl ester, epoxy, or polyester. Thermoplastic resins have also shown promising performance, and of specific interest for post-processing formability and recyclability [68]. Fibers provide the tensile strength and stiffness, and the resin acts as a binder providing load transfer to the adjacent fibers. The role of an FRP reinforcement manufacturer is to combine fibers and resin into pultruded composite bars. During pultrusion, fibers are coated with resin and drawn through a heated die from which they emerge as a semi-final product. Then, various surface preparation techniques can be employed to enhance the bond of the FRP bar to the concrete, including sand coating, surface deformation, helical grooving, or combinations of these methods. Other manufacturing techniques include combining a number of small-diameter composite bars which can be twisted into a single strand providing a flexible configuration (similar to steel 7-wire strand) which can be coiled for shipping and handling, allowing for long precast pre-tensioned and post-tensioned concrete applications [69, 70]. Being a non-ferrous material, FRP is non-corrosive and impervious to chloride attack.

Applications

Given these attributes and recognition that corrosion is a significant challenge for much of the built environment, this paper attempts to address a small, but high-risk subset of transportation infrastructure predominantly within the splash zone as defined in AASHTO [1]. The risk of chloride penetration and migration through concrete is typically higher for components of coastal RC structures in direct contact with, or in close proximity to seawater. In these locations as previously highlighted, the propensity for chloride build-up at the concrete surface results in higher concentration gradients, which are favorable for diffusion. In addition, chlorides can rapidly penetrate the concrete if cracks are present. Following are examples of such components that would benefit the most from the use of CR-solutions, beyond bridge decks which have been adequately covered by others as referenced in the Validation Examples section.

Seawalls

RC seawalls typically consist of precast wall panels, cast-in-place bulkheads, and tie-back systems when needed. Seawall elements located in the splash zone commonly require premature repairs or replacement due to severe damage caused by the corrosion of carbon-steel reinforcement. Use of steel sheet pile walls is typically discouraged for long-term coastal applications due to the extensive thru-thickness section loss, perforation and blistering of protective coatings that occurs in the splash zone [71, 72]. Seawalls are utilized extensively along or near coastal areas for bridge infrastructure as well as protection of coastal commercial and residential properties [73]. Figures 2 and 3 show typical examples of severe corrosion damage that can be avoided using CR-solutions.

Bridge foundations

Bridge foundation elements in the splash zone are also subject to high corrosion risk, even when designed with considerations for environmental exposure. With carbon-steel reinforcement, additional life-cycle costs are incurred not only by the necessity of initial protection strategies (enhanced concrete mix design and concrete cover thickness), but also the mitigation of corrosion damage on existing elements. In most cases and within limitations, appropriately designed cathodic protection (CP) systems can extend the life of piles,

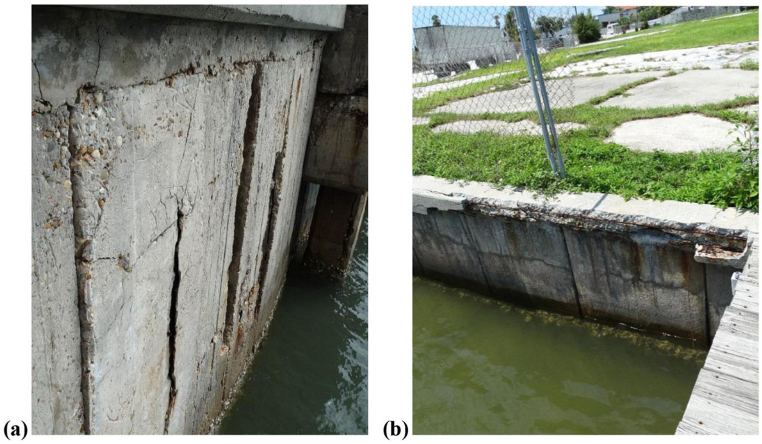

Fig. 2 Typical examples of severe corrosion damage on concrete seawalls [95]

footings, columns, etc. with corrosion damage until complete replacement is required. However, CP systems incur significant costs for monitoring and maintenance to be effective. The design of bridge foundations with CR-solutions would eliminate the need and cost of additional corrosion prevention and mitigation strategies.

Low-level superstructures

The superstructure components of bridges (decks or slabs, girders, and traffic railings) over waterways with high chloride concentrations, are desirably elevated above the splash zone as much as possible. Where provision of higher member elevations is not physically or economically feasible, steel-RC has proven to be very susceptible to corrosion damage. Moreover, corrosion mitigation strategies such as cathodic protection can be very complicated, and often improbable, for such elements due to the complex layout of reinforcing steel. Therefore, CR-solutions for these elements are more reliable for achieving desirable structural longevity of low-elevation superstructure elements.

Validation examples

Several examples are presented with supporting archival literature references showing the viability and suitability of FRP composite structures in the coastal environment. The first six projects are the earliest known examples of FRP-RC or PC bridge component construction, while the last three bridges highlight more recent examples for entire bridges utilizing predominantly FRP reinforcing and/or prestressed concrete. It has been reported that more than 270 bridges have been completed using FRP reinforcement in the US and Canada [74], and more than 23 of these include CFRP prestressing in the US [75].

Ulenbergstrasse bridge, Düsseldorf, Germany 1986 (GFRP-PC)

The world's first vehicular bridge using FRP E-glass tendons with polyester resin and polyamide coating for protection against chemical and mechanical attack [76].

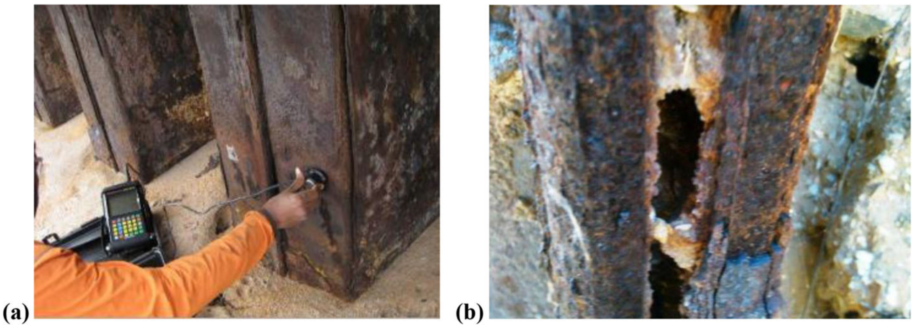

Fig. 3 Typical examples of severe corrosion damage on steel sheetpile seawalls [71]: **a** Section thickness testing; **b** Perforation at joint

Shinmiya bridge, Japan 1988 (CFCC-PC)

The world's first Carbon Fiber Composite Cable (CFCC) prestressed concrete bridge located adjacent to the Sea of Japan. This bridge was constructed as a replacement for a 21-year old prestressed concrete bridge suffering severe corrosion deterioration. Additional prestressed beams were set adjacent to the structure for in-place weathering and then tested to destruction in 1994 and 2017. The flexural strengths exceeded the original beams by 20%–25%, possibly due to concrete strength gain and the compression-controlled failure mode [77].

Beddington Trail bridge, Calgary, Alberta 1993 (CFCC & CFRP-PC)

The first highway bridge in North American with FRP prestressing. This is a two-span skewed bridge using CFCC (helically twisted) tendons and Leadline (straight single) strands for precast/pretensioned bulb-T girders [70]. Three girder lines contained CFCC and three CFRP Leadline strands to match the remaining conventional prestressed girders.

Hall's Harbor Wharf, bay of Fundy, Nova Scotia 1999 (GFRP-RC)

The Hall's Harbor Wharf was the first marine structure in Canada to be built using Intelligent Sensing for Innovative Structures (ISIS Canada) technology and design concepts [78]. The wharf, located on the Bay of Fundy shore in Nova Scotia, comprises steel-free precast concrete panels with GFRP bars and concrete pile cap beams reinforced with a hybrid GFRP-steel bar system.

McKinleyville bridge, West Virginia, 1998 (GFRP-RC)

McKinleyville Bridge was one of the first bridge decks to use GFRP rebar in the US. GFRP bars were extracted from the bridge after 15 years of service life, showing good durability performance [79]. Other bridges that followed include Gills Creek Bridge, O'Fallon Park Bridge, Salem Ave Bridge, Bettendorf Bridge, Cuyahoga County Bridge, Sierrita de la Cruz, Thayer Road Bridge, Bourbon County Bridge. The ACI Strategic Development Council sponsored a durability review of the GFRP bars in 11 of these early bridges to assess the performance after 15 to 20-year of service life [80]. Similar to earlier studies on Canadian bridges [81–83], the standard ASTM accelerated aging tests were found to be very conservative when compared to in-service performance strength testing.

Val-Alain bridge, Quebec 2004 (GFRP-RC)

Val-Alain Bridge was the first completely steel-free deck in Canada. In 2015, concrete cores were taken, and the encapsulated GFRP bars were evaluated to assess durability [84]. Other early Canadian bridges with partial GFRP reinforcing replacement include Joffre Bridge [85], Chathman Bridge [86], Crowchild Trail Bridge [87], and Waterloo Creek Bridge [88]. Additional long-term durability investigations are also documented for the 3rd Concession Rd. Bridge over Highway 401 [89, 90].

Innovation Bridge, Coral Gables, FL 2016 (GFRP-RC, BFRP-RC & CFRP-PC)

Located on the University of Miami campus in Coral Gables (FL) the Innovation Bridge is a 65-ft. long single span PC bridge. The bridge serves as a pedestrian passageway and comprises a variety of non-corrosive reinforcement solutions including CFRP prestressing strands, GFRP bars, and the first deployment of BFRP closed stirrups and preassembled reinforcement cages in bridges. The structure is an entirely steel-free structure designed for resilience and durability in aggressive subtropical exposure [91, 92].

Halls River bridge, Homosassa, FL 2019 (GFRP-RC & CFRP-PC)

Halls River Bridge is a five-span vehicular bridge constructed between 2016 and 2019, using entirely CR-solutions and mostly FRP reinforcement. The structure includes CFRP-PC bearing piles, CFRP-PC/GFRP-RC sheet piles, hybrid Carbon-Steel-PC/GFRP-RC sheet piles, GFRP-RC pile bent caps and bulkhead caps, Hybrid Composite Beams with a GFRP-RC bridge deck, GFRP-RC traffic railings, GFRP-RC approach slabs, and a GFRP-RC gravity wall. The unprecedented variety and completeness of the material and structural solutions deployed make the Halls River Bridge a valuable source for data. Monitoring protocols were implemented at the design and construction stages and will be continued through the early service life of the structure [93]. A Life-Cycle Cost analysis was later performed by [30, 31], proving a complete FRP-RC/PC design to be the least impacting solution from both an economic and environmental perspective over an estimated service life of 100-years.

Innovation Dock, Coral Gables, FL 2019 (GFRP-RC & BFRP-RC)

The Innovation Dock (*iDock*) is a full replacement of a marine boat dock damaged by hurricane Irma. The new structure used PC members partially mixed with seawater and reinforced with GFRP and BFRP bars [94] and pioneered the deployment of Accelerated Bridge Construction (ABC) methods using Prefabricated Bridge Elements and Systems (PBES) for coastal structures.

NE 23rd avenue over Ibis waterway, City of lighthouse point, FL 2020 (GFRP-RC/PC & CFRP-PC)

The NE 23rd Ave. bridge is the first GFRP-RC three-span continuous flat-slab vehicular bridge in the US. The abutments also include the first soldier-pile bulkhead-seawall with GFRP-RC precast panels, two demonstration 18-in. square GFRP-PC piles in the wing walls, and combined CFRP-PC bearing/soldier-piles for the end bents. The bridge includes GFRP-RC for cast-in-place end bents, intermediate bent caps, and bulkhead caps. Early construction activities demonstrated swage-coupling [95] and partial prestressing [70] of GFRP bars that were coiled during shipping to the precast yard, for fabrication of two seawall soldier-piles (Fig. 4a & b). Construction of the bulkhead-seawall was completed in December 2020, and the bridge is expected to be completed by early 2021.

US-41 northbound over North Creek, osprey, FL 2020 (GFRP-RC)

The US-41 (Florida State Road 5) bridge is the first GFRP-RC two-span continuous flat-slab highway bridge in the US. It is the second soldier-pile bulkhead-seawall in Florida with GFRP-RC precast panels, but utilizes larger 24-in. square CR-prestressed piles compared to 23rd Ave. NE. For this project, the piling precaster/contractor choose to utilize 2205 duplex alloy stainless-steel prestressing strands (ASTM [96]) in lieu of the CFRP option, as permitted per FDOT's Standard Specification [97], but only when highly reaction pozzolans are added to the concrete mix. The bridge includes a GFRP-RC cast-in-place superstructure (Fig. 4c), traffic railings, and bulkhead seawall caps. Construction is expected to be completed by early 2021 [98].

Cost comparisons for FRP-RC solutions

There is a paucity of rigorous cost comparisons between conventional structural materials versus FRP-RC and PC solutions. Furthermore, academic or industry consensus on methodologies, unit rates, maintenance costs, frequency, escalation, and risk factors need to be established for reliable comparisons. The relative benefits of sustainability and adaption strategies against future environmental risks are also yet to be reliably established. Recent published studies that support long-term economical and/or environmental preferences for FRP-RC/PC solutions above HCR or conventional designs utilize Life-Cycle Cost (LCC) analysis and Life Cycle Assessment (LCA), respectively.

Younis et al. [99] performed LCC analysis to verify the cost savings associated with GFRP reinforced using environmentally friendly structural concrete incorporating seawater and recycled coarse aggregates, and GFRP reinforcement. The design alternatives were compared for a conceptual high-rise building, using conventional concrete with carbon-steel reinforcement, against seawater-mixed, recycled-aggregate, GFRP-reinforced concrete. Younis et al. [100] also compared the long-term cost performance among four reinforcing materials: conventional carbon-steel; epoxy-coated carbon-steel; stainless-steels; and GFRP reinforcing, for a concrete water chlorination tank. Both studies had preferential outcomes for the GFRP reinforced alternative.

Cadenazzi et al. [30, 31] performed LCC analysis and LCA on the Halls River Bridge using conceptual alternative designs with both conventional and HCR materials. The findings implied that the FRP-RC/PC solutions where typically preferential. The LCC analysis preferential solution was somewhat dependent on the choice of the discount rate which attempts to address inflation and the cost of capital financing. Cadenazzi et al. [101] expanded on the LCC analysis with a probabilistic approach in an attempt improve risk evaluation for many of the LCC variables (discount rate, reconstruction cost, maintenance timing, frequency, and cost). Similarly, probabilistic analysis of the rates of corrosion and

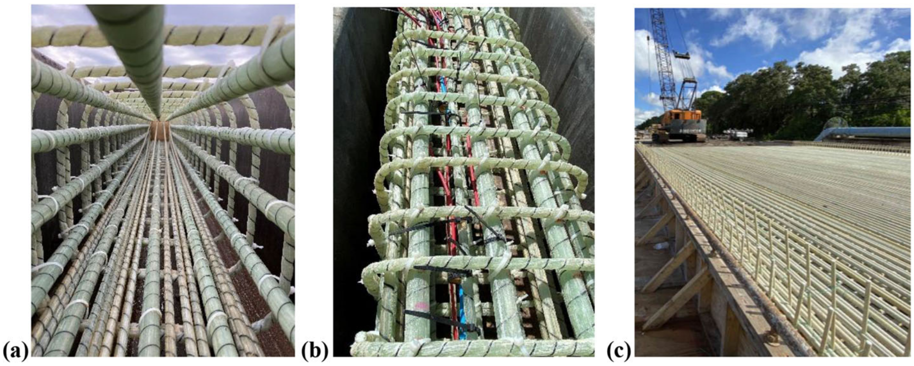

Fig. 4 Typical examples of new GFRP-RC/PC construction: **a** Soldier pile fabrication before tensioning, and **b** after tensioning #4 bar strands [68]; **c** CIP flat-slab bridge conservative reinforcing layout

structural effects [102] may help to refine the reliability (timing and frequency) of corrosion mitigation intervention estimation for conventional materials in future studies. The LCA looked at five impact categories (Ozone Depletion Potential, Global Warming Potential, Photochemical Oxidant Creation Potential, Acidification Potential, and Eutrophication Potential) with Global Warming and Eutrophication impacts favoring FRP-RC/PC solutions, and SS-RC/PC (HCR) for the other impacts under the cradle-to-grave scenario. Additional comparative studies in both LCC and LCA should be pursued under differing environmental conditions and scale, to provide designers and owners with better decision-making tools.

Conclusion

Over more than 30 years of field applications in bridge structures, FRP reinforcement has proved to be a reliable and durable material, able to fulfill the owners' demand for increased service-life, reduced maintenance costs, resilience, and sustainability. Considering that almost 300 bridges have been completed using FRP reinforcement and prestressing in the US and Canada, there is substantial validation available for the structural engineering community. Embracing this cost-effective solution would avoid much of the ever-present risk of corrosion and future preservation efforts that are currently needed for coastal bridges and similarly exposed infrastructure. Additional comparative studies on contemporary structures using both LCC and LCA are important for holistically identifying the optimal economic and environmental solutions for sustainable designs.

Abbreviations

AASHTO : American Association of State Highway and Transportation Officials; ACMA: American Composite Manufacturers Association; ASCE: American Society of Civil Engineers; BFRP: Carbon Fiber-Reinforced Polymer; CBO: Congressional Budget Office; CSA: Canadian Standards Association; CFCC: Carbon Fiber Composite Cable; CFRP: Carbon Fiber-Reinforced Polymer; CP: Cathodic Protection; CR-: Corrosion-Resistant; EDC: Every Day Counts (FHWA); FDOT: Florida Department of Transportation; FHWA: Federal Highway Administration; *fib*: Fédération Internationale du Béton; FRP: Fiber-Reinforced Polymer; GFRP: Glass Fiber-Reinforced Polymer; GOST: Governmental Standards (Russian Federation); IBRC: Innovative Bridge Research and Construction; LTBP: Long-Term Bridge Preservation; MR&R: Maintenance, Repair and Rehabilitation; NASEM: National Academies of Science, Engineering, and Medicine; PBES: Prefabricated Bridge Elements and Systems; PC: Prestressed Concrete; RC: Reinforced Concrete; UTC: University Transportation Centers

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Authors' contributions

SN conceived the manuscript, provided the outline, collected historical content, quantification of corrosion effects, and presented an abbreviate version at the 2019 Bridge Engineering Institute Conference. CK contributed to the corrosion and mitigation, and seawall content and photos. MR and AN contributed the contemporary validation example projects and the McKinleyville Bridge/ACI-SDC investigations. All authors were involved in editorial review of the final paper. The author(s) read and approved the final manuscript.

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Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Competing interests

The authors declare that they have no competing interests.

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