

# Flagler Beach GFRP-RC Secant-Pile Seawall for Hurricane Resilience, Durability and Efficiency



Christian C. Steputat, Steven Nolan, Marco Rossini, and Antonio Nanni

## 1 Introduction

An innovative, resilient yet sustainable, 1.5 km-long, low-impact, buried Secant-Pile Seawall/Bulkhead, was completed in July 2019, after less than 5 months of active construction along the ocean-side shoulder region of State Highway A1A, north of Flagler Beach, Florida, USA. Sand dune restoration, landscaping, roadway drainage and paving continued through the end of the year, and this coastal highway protection system was already tested when Hurricane Dorian paralleled Florida's East Coast, in early September 2019. The utilization of advanced construction materials in designing and analyzing is essential, especially when building sustainable infrastructure (relatively green and resilient), while equally important is analyzing the service-life cost savings, which is typically a substantial fiscal return on program investment. The Glass Fiber-Reinforced Polymer (GFRP) Reinforced Concrete (RC) general characteristics consist of bars that are impervious to chloride ion and low pH chemical attack, have a tensile strength of approximately twice the strength of steel, have a weight of one quarter that of steel bars, are transparent to magnetic fields and

---

C. C. Steputat (✉) · M. Rossini · A. Nanni  
University of Miami, Department of Civil and Architectural Engineering, 1251 Memorial Drive,  
MEB Room 325, Coral Gables, Florida 33146-0630, USA  
e-mail: [csteputat@miami.edu](mailto:csteputat@miami.edu)

M. Rossini  
e-mail: [mxr1465@miami.edu](mailto:mxr1465@miami.edu)

A. Nanni  
e-mail: [nanni@miami.edu](mailto:nanni@miami.edu)

S. Nolan  
Florida Department of Transportation, State Structures Design Office, 605 Suwannee Street,  
Tallahassee, FL 32399, USA  
e-mail: [steven.nolan@dot.state.fl.us](mailto:steven.nolan@dot.state.fl.us)

radio frequencies, have low electrical and thermal conductivity and induce reduced breaking and cracking of concrete, exposed to some cyclic loading conditions. These attributes favor widespread GFRP-RC use in the near future.

The subject GFRP-RC Secant-Pile buried Seawall/Bulkhead is located in the northeastern section of Flagler County, Florida, and extends a total of 1.5 km along the east side of State Road A1A (SR-A1A), at Flagler/Beverly Beach, USA, beginning at North 18th Street [STA 825 + 60.00 (30.00 RT)], and ending at Osprey Drive [STA 874 + 81.82 (30.00 RT)], respectively.

The timing of the Hurricane Dorian (2019) event shortly after the completion of the Secant-Pile seawall highlights the potential risk for much of the coastal infrastructure to the increasingly frequent extreme-weather events, sea-level rise and the strategic importance of adaptive planning in an era of accelerating planet change. An ever-increasing worldwide need for resilient, innovative, yet sustainable infrastructure is becoming the expectation and will play a significant role in long-term effectiveness, including Life-cycle Cost Analysis (LCCA) savings (Fig. 1).



**Fig. 1** Path of Hurricane Dorian (2019), paralleling the Florida East Coast

## **2 SR-A1A GFRP Secant-Pile Seawall/Bulkhead Intent and Estimated Unit Costs**

The implementation of GFRP reinforcing to this Secant-Pile Seawall/Bulkhead project makes this project even more unique and interesting in an engineering sense, since it is the first of a kind in the State of Florida and provides relative ease of construction due to the lighter weight of the GFRP rebars compared to conventional steel, drastically reduced assembly times, elimination of corrosion for this aggressive coastal environment application, anticipated significant service-life extension and reduced life-cycle costs for the structure, by drastically reducing the need for any maintenance and costly repetitive repairs and rehabilitation. Even without conducting a full Life-Cycle Cost (LCC) and Life-Cycle Analysis (LCA) comparison against traditional construction methods and materials, the economic and environmental advantages of the selected GFRP-RC Secant-Pile Seawall/Bulkhead alternative are obvious.

The SR-A1A Seawall/Bulkhead project design considerations include corrosion-resistant reinforcing (GFRP) in lieu of the typical carbon-steel (black) rebar, provision for a 100-Year Scour-Depth to eliminate the need for Toe-Protection, 0.91 m diameter by 10.97 m long GFRP structurally reinforced Auger-Cast Piles as well as 0.91 m diameter by 5.49 m long Tensile Center-Bar Reinforced Auger-Cast Piles. The GFRP rebar is composed of EC-R glass fibers embedded in a vinylester resin. Some of the advantages to be noted are that the fibers provide strength and durability, and the resin bonds fibers together, transferring load between fibers and providing additional protection from environmental factors and mechanical abrasion. The GFRP structurally reinforced Secant-Pile Seawall/Bulkhead was the preferred alternative, due to its corrosion-resistant reinforcing (GFRP), relative ease of construction, the presence of shallow and dense coquina rock and buried boulders that could present difficulties while driving or jetting sheeting, a narrower construction footprint requiring only one lane closure and no tie-back anchorage systems, speed of installation with no predrilling requirements, all resulting in reduced vibration and noise effects on adjacent structures and less of an impact to the local community and natural habitat. Among the aforementioned advantages of selecting the GFRP option, the design teams estimate for this project, with respect to the use of a traditional steel reinforced auger-cast pile, equates to \$628/m of pile length installed, while the GFRP-reinforced concrete auger-cast piles equate to \$687/m of pile length installed.

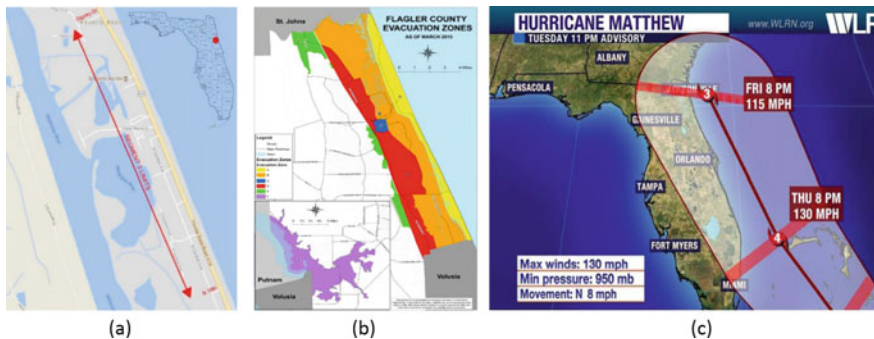
Additionally, for approximate cost comparison considerations, assume a 75-Year Service Life for the carbon-steel reinforced concrete (CS-RC) which equates to a Nominal Annual Cost (NAC) of \$8.37/Year/m, while a 100-Year (Minimum) Service Life for the GFRP reinforced concrete (RC) equates to a NAC of \$6.86/Year/m. Although no discount rate is included in developing the NAC, as is typically used for the more conventional Equivalent Annual Cost (EAC), no maintenance costs nor environmental benefits are considered either. This simplification of the LCC analysis proposed by the authors is considered reasonable for comparison of these types of systems, given the differences in design like maintenance expectations, and the

minimal effect of the real discount rate applicable to publicly funded infrastructure (Cadenazzi et al. 2019). Resilient and sustainable designs utilizing Glass or Basalt FRP structural reinforcing, especially for Seawall/Bulkheads and Pile/Panel-Wall-System applications, are likely to become a more common solution in the near future. Encouragement and support of educational (technology transfer) activities for contractors and design professionals are important for broad, consistent and reliable deployment. The anticipated LCC savings, while utilizing GFRP-RC, are estimated at approximately 62–70%, over the expected 100-Year service life of critical infrastructure, components or systems elements.

### 3 Effects of Hurricane Matthew (2016)—The Need to Fortify SR-A1A

The Florida seaside community of Flagler Beach, Florida, USA, was severely impacted in 2016 by Hurricane Matthew, which caused estimated damages of \$16.47 billion in 2016 USD (Wikipedia, NOAA, Hurricane Matthew 2016). The intent of this SR-A1A Flagler Beach (Segment 3) Secant-Pile Seawall/Bulkhead project is to provide storm-related protection and fortification for the highway from increasingly frequent and severe storm-related wave action and erosion activity, as well as possible localized and globalized storm scour conditions. The protection of this highway becomes especially important during Hurricane seasons, since it is designated as an Evacuation ZONE “A” and is essential for storm-recovery activities.

The illustrations in Fig. 2 show the Segment-3 limits, Evacuation Zone-A (in yellow) and the probability cone of influence for Hurricane Matthew (2016), with respect to Flagler Beach, Florida, USA.



**Fig. 2** a Boundary Limits of SR-A1A Segment-3, b SR-A1A Flagler Beach Evacuation Zone-A, c Cone of Influence of Hurricane Matthew (2016)

## **4 Existing Site Conditions, Soils and Coastal (Marine) Environment Conditions**

The existing soil conditions, for the designed length of 1.5 km of this Secant-Pile wall section, did not necessitate unusual drilling operation requirements. Some softer and harder material was encountered throughout but did not alter operational requirements. The time was monitored for each primary and secondary pile and accounted for the soil characteristics and varying soil densities. Isolated buried rocks and boulders and/or broken concrete may have existed along the proposed wall alignment and were removed whenever encountered. It should be noted that no layers of very dense cemented sand were encountered at this site, therefore the Secant-Pile Seawall installation proceeded very smoothly, yet fast-paced, and the speed of installation was predominantly controlled by the concrete grout supply availability. Drilling speeds of Secant-Piles were field-measured and varied by only approximately 56%-64% between “best” (loose soil) and “worst” (hard soil) locations. In general terms of review, prior to the GFRP-RC Secant-Pile seawall construction initiation, artesian conditions were not noted during the Geotechnical Engineering phase of this project. However, based on the review of the U.S. Geological Survey Map (USGS 2014) for the construction project area, the elevation of the artesian head is estimated to be approximately + 1.22 m to + 2.74 m NAVD 88. Therefore, temporary casing and other suitable groundwater and hydrogeological methods were utilized to control the artesian head levels, to a head elevation of not less than + 2.74 m NAVD 88. Furthermore, the coordination of the existing grading and grading profiles, along the length of the wall, is very important and can be critical at times. The lead author observed the fill-placement in lifts, which is required for this project, prior to the Secant-Pile Seawall installation to achieve the desired and designed “Secant-Pile-top” elevations. The FDOT Environmental Classification for this Secant-Pile Seawall is Extremely Aggressive, due to the presence of Chlorides.

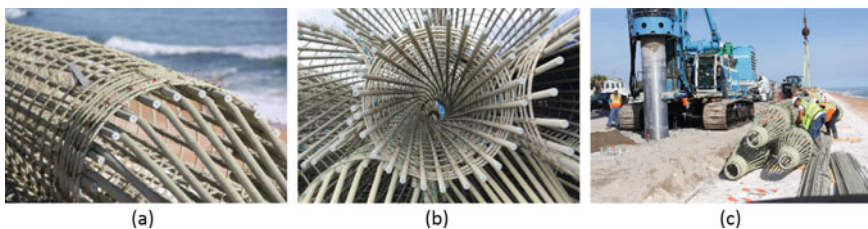
## **5 GFRP-RC Secant-Pile Drilled Shafts with LCC-Benefits for SR-A1A Protection**

In order to fortify SR-A1A and better protect it against future storm events, the preferred design alternative required the installation of a Secant-Pile Seawall, which can be best described as a series of interconnecting Auger-Cast Drilled Shafts. The project required a total of 1847 Secant-Piles placed to specified tolerances. The uniqueness of this project is the utilization of GFRP rebars, in place of the conventional carbon-steel rebars, which are sensitive to corrosion. Essentially, this will result in a non-corroding structure that will significantly extend the service life, resulting in significant maintenance and repair savings over the Life Cycle of the structure. Hurricane Matthew (2016) caused severe damage in the Caribbean (Haiti), as well as widespread damage in the southeastern United States, yet luckily remained offshore

paralleling the Floridan coastline. Hurricane Matthew (2016) became a Category 5 Hurricane (the first since Hurricane Felix in 2007) with a minimum recorded barometric pressure of 934 mbar (hPa), forming on September 28, 2016, and dissipating on October 10, 2016, with the highest 1-min sustained winds recorded at 270 km/h and a reported 603 fatalities and is now estimated to have caused damages of \$16.47 billion in 2016 USD (Wikipedia, NOAA, Hurricane Matthew 2016). The Northbound Lanes (within Evacuation Zone A) of State Road A1A in Flagler County, near the Flagler Beach Pier, were washed out for more than 1.6 km, by Hurricane Matthew, in 2016, which now is the subject of this fortified Secant-Pile Seawall/Bulkhead Structure, hidden beneath the newly “re-established” dune system. As previously discussed, severe corrosion damage to a previously existing steel sheet pile bulkhead and extensive erosion damage to the adjacent sand dune system required immediate intervention, in order to avoid future closures of SR-A1A, near Flagler Beach, Florida. This need for immediate intervention was accelerated drastically, after an increasing frequency of extreme weather conditions and sea-level changes, likely associated with global warming, resulting in the most recent and severe damage from Hurricane Matthew in 2016, and a near miss from Hurricane Dorian (2019)—which luckily remained offshore, but still caused significant sand dune erosion (up to 4 m in some locations) in front of the newly constructed protection system (Fig. 3).

Additionally, Life-Cycle Analysis (LCA) studies show the environmental benefits of GFRP reinforced concrete beyond the extended service life and do consider the mutual beneficial transportation and work process efficiencies, among others. Five commonly assessed parameters under ISO 14040 and 14,044 that warrant consideration are listed below:

- Ozone Depletion Potential
- Global Warming Potential
- Photochemical Oxidant Creation Potential
- Acidification Potential
- Eutrophication Potential.



**Fig. 3** a Primary-pile cage showing GFRP toe-assembly, b View into primary-pile cage with spiral-reinforcing, c Primary-pile cage lifting—flexibility and lightweight of GFRP cage-assemblies for primary piles is a superb benefit

The GFRP flexibility and superior performance characteristics, with respect to weight, tensile strength and corrosion resistance, are some of the reasons for the rapid completion of this significant SR-A1A project.

Studies have been initiated to study the degree of degradation of the GFRP bars, as attributed to UV radiation exposure, and other studies of significant parameters of interest beyond alkali and seawater sensitivity. Future work by the authors based on studies from this project includes Life-Cycle Cost (LCC) and Life-Cycle Analysis (LCA) comparisons against traditional construction means and methods to showcase the economic and environmental advantages of the GFRP-RC alternative. Further studies at the University of Miami, Department of Civil, Architectural and Environmental Engineering, include the SEAHIVE system, which combines wave attenuation and ecological habitat, utilizing resilient and sustainable structural materials.

## **6 Infrastructure Protection via GFRP—Confirmed Laboratory Test Results (FDOT)**

The evaluation of fiber-reinforced polymer (FRP) reinforcing bars was conducted in accordance with FDOT Section 932–3. The glass fiber-reinforced polymer (GFRP) rebars tested to date meet the requirements as set forth within Florida Department of Transportation (FDOT) Non-metallic Accessory Materials for Concrete Pavement and Concrete Structures, Section 932–3. The experimental testing program was conducted at the University of Miami, Civil, Architectural and Environmental Engineering Advanced Structures and Materials Laboratory (SML), which maintains a quality system [QA/QC], in compliance with ISO 17025–2019, which is accredited under the International Accreditation Services (IAS) and is a qualified testing laboratory for the Florida Department of Transportation [FDOT]. The glass fiber-reinforced polymer (GFRP) bars tested meet the requirements as set forth within the Florida Department of Transportation (FDOT) Non-metallic Accessory Materials for Concrete Pavement and Concrete Structures, Section 932–3. It is this “fast-paced”, on-schedule, GFRP Seawall/Bulkhead project that will lead to additional GFRP projects that will further fortify our coastlines in a resilient, sustainable, durable, yet efficient way without significant impact or alteration to our beloved coastlines.

## **7 Life-Cycle Cost Analysis (LCCA) Methodology for SR-A1A GFRP-RC Seawall**

Typically, the purpose of an LCCA for this SR-A1A project is to establish the overall project cost alternatives and to assist in selecting the best possible design that guarantees that the facility will deliver the lowest overall operating cost for the owner, yet

has to be very consistent with its quality of service and functional requirements. The LCCA should be performed early in the design process, so that the design can still be refined, to ensure a reduction in life-cycle costs (LCC). Operating schedules and standards of maintenance can vary significantly among infrastructure components, so it is essential to utilize sound engineering reasoning, during the establishment of these costs. Upon completion of identifying all the applicable cost components by year and amount, they need to be discounted to present value.

$$LCC = \{ [Inv.] + [Repl.] - [Res.] \} + \{ [Ener.] + [Water] + [OM\&R] + [Add.] \} \quad (1)$$

where:

<b>LCC</b>	Total Life-Cycle Costs (LCC) in Present Value [P.V.] dollars of a given Alternative.
<b>Inv.</b>	P.V. Investment Costs [if incurred at Base Date, they need not be Discounted].
<b>Repl.</b>	P.V. Capital Replacement Costs.
<b>Res.</b>	P.V. Residual Value [Resale Value, Salvage Value] less [Disposal Costs].
<b>Ener.</b>	P.V. of Energy Costs.
<b>Water</b>	P.V. of Water Costs.
<b>OM&amp;R</b>	P.V. of Non-Fuel Operating, Maintenance and Repair Costs.
<b>Add.</b>	P.V. of Additional Costs [e.g. Contract Costs for ESPCs or UESCs].

For this 1.5 km-long, SR-A1A buried Secant-Pile Seawall/Bulkhead project, an estimated LCC savings of 58–70% are anticipated over its life cycle. Further details will be disclosed upon research completion.

## 8 Update to AASHTO Bridge Design Guide Specifications for GFRP-RC

The development of a bridge-comprehensive national standard is crucial to fostering the deployment of durable GFRP-RC structures. To respond to this demand, a task force of researchers, practitioners and transportation officials has developed a draft for the second edition of the *AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete*. The document was published by AASHTO in December 2018 (AASHTO 2018a, b). Compared to the first edition of the guidelines (AASHTO 2009), changes were introduced to reflect the current state of the art. The goals included making the provisions more rational, offsetting some over-conservativeness and making the design approach consistent with the *AASHTO LRFD Bridge Design Specifications* for traditional construction materials (AASHTO 2017).



**Table 1** Design parameters for GFRP-RC

Parameter/Factor	fib	CSA	ACI	AASHTO GFRP	
	2013	2014	2015	2009	2018
$\phi_c$	0.67	0.75	0.65	0.65	0.75
$\phi_t$	0.80	0.55	0.55	0.55	0.55
$C_E$	n/a <sup>(1)</sup>	1.00	0.70	0.70	0.70
$C_c$	0.30	0.25	0.20	0.20	0.30
$C_f$	0.50	0.25	0.20	0.20	0.25
$C_b$	0.71 <sup>(2)</sup>	1.00	0.71	0.71	0.83

<sup>(1)</sup>Alternative approach per *fib* bulletin 40 (Fib 2007)

<sup>(2)</sup>From *fib* bulletin 40 (Fib 2007).

## 8.1 GFRP-RC Design Parameters and Resistance Factors

Table 1 provides a summary of design parameters as reported by international design guidelines along with the values adopted in the first and second editions of AASHTO (2009, 2018a, b).

The flexural strength reduction factor for compression-controlled failures ( $\phi_c$ ) is raised from 0.65 to 0.75 (15%) with respect to the first edition. The creep rupture reduction factor ( $C_c$ ) is raised from 0.20 to 0.30 (50%) with respect to the first edition. The value is suggested by recent research findings (Benmokrane et al. 2019, Rossini et al. 2019c). The fatigue reduction factor ( $C_f$ ) is raised from 0.20 to 0.25 (25%) for alignment with international standards (Fib 2013; CSA 2014). The bond reduction factor ( $C_b$ ) is defined as the inverse of the bond coefficient ( $k_b$ ) and is raised from 0.71 to 0.83. The value is more conservative with respect to other international guidelines (CSA 2014).

## 8.2 GFRP-RC Member Design Provisions

A GFRP-RC member must be designed against several Ultimate Limit States (ULSs) and Service Limit States (SLSs). ULSs include compression failure of the concrete or tension failure of the GFRP bars under ultimate load. Furthermore, GFRP bars can experience creep rupture under sustained load, and fatigue rupture under cyclic load. Shear failure must be considered as well, and an algorithm based on the Modified Compression Field Theory (MCFT) is specified. SLSs include a limit on deflection ( $L/800$  for vehicular bridges), a limit on crack width (0.7 mm) and a limit on concrete stresses under sustained load ( $0.45 f_c'$ ). The relatively low stiffness of GFRP bars may result in SLSs governing the design.

### 8.3 Implications on the State of the Practice

The second edition of *AASHTO Bridge Design Guide Specifications for GFRP-Reinforced Concrete* (AASHTO 2018a, b) covers the design of all the members of a reinforced concrete bridge including, but not limited to bridge decks, girders, bent caps, piers, pier caps, piles, approach slabs, shallow foundations and retaining walls. These provisions have been successfully deployed in the design of several structures including the Innovation Bridge at the University of Miami, Florida, and the i-Dock, in Miami, Florida, a marine dock using accelerated bridge-type of construction (ABC) and concrete mixed with seawater.

Projections show that using the second edition of the specifications to design a bridge deck reduces the amount of GFRP reinforcement by approximately 25% resulting in an initial cost that is 10% higher than with respect to a steel-reinforced solution, and a life-cycle-cost savings of more than 40%, respectively.

We look forward to the next decade of innovation and changes, especially with respect to GFRP and BFRP and hope to contribute to and educate the construction industry at large, to embrace this technology.

**Acknowledgements** Dr. Rossini's affiliation to the University of Miami ended in December 2019, as of his graduation. The information and views set out in this article are those of the authors and do not necessarily reflect the official opinion of the European Commission.

## References

- AASHTO (2009) LRFD bridge design guide specifications for GFRP-reinforced concrete bridge decks and traffic railings, 1st edn. American Association of State Highway and Transportation Officials, Washington, DC
- AASHTO (2018a) AASHTO LRFD bridge design specification, 8th edn. American Association of State Highway and Transportation Officials, Washington, DC, p 438
- AASHTO (2018b) LRFD bridge design guide specifications for GFRP-reinforced concrete, 2nd edn. American Association of State Highway and Transportation Officials, Washington, DC
- ACI Committee 440 (2015) 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, p 83
- Benmokrane B, Brown VL, Mohamed K, Nanni A, Rossini M, Shield C (2019) Creep-rupture limit for GFRP bars subjected to sustained loads. *J Compos Constr* 23(6):06019001(1–7). [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000971](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000971)
- Cadenazzi T, Dotelli G, Rossini M, Nolan S, Nanni A (2019) Life-cycle cost and life-cycle assessment analysis at the design stage of a fiber-reinforced polymer-reinforced concrete bridge in Florida. *Adv Civ Eng Mater*. ASTM International. <https://doi.org/10.1520/ACEM20180113>
- CSA (2014) Canadian highway bridge design code. CAN/CSA-S6–14. Mississauga, CSA Group, ON
- FDOT (2018c) Structures Manual, Florida Department of Transportation, Tallahassee, FL
- FDOT (2018b) Standard specifications for road and bridge construction, Florida Department of Transportation, Tallahassee, Florida, p 1213
- Fib (2007) FRP reinforcement in RC structures. Lausanne, fédération internationale du béton, CH

- Fib (2013) Model code for concrete structures 2010. Berlin, Wilhelm Ernst & Sohn, DE
- FDOT (2018a) FDOT design manual, Florida Department of Transportation, Tallahassee, FL.  
<https://www.fdot.gov/roadway/fdm/2018fdm.shtm>
- USGS (2014) Potentiometric Surface of the Upper Floridan Aquifer in the St. Johns River Water Management District [SJRWMD] and Vicinity, Florida”, U.S. Geological Survey Map