

Substitution of Steel Reinforcement with GFRP in Bridge Decks: Impact on Materials, Additives, and Costs

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Abstract — Previous research of GRFP reinforcement as an alternative to steel re-bar for decks has shown better durability in highly corrosive environments [1], [2]. This project showed an alternative deck design to an ongoing design project of the Puerto Rico Highway Authority substituting traditional R/C deck design with GRFP reinforcement. It shows that the alternative is cost effective for construction and can be implemented in Puerto Rico for bridges in zones considered of higher corrosion risk as those close to marine environments as a.

Key Terms — Cost, Innovation, Resilience, Sustainability,

DESIGN STRATEGY

In this case study an alternative Glass Reinforced Fiber Polymer (GRFP) reinforced concrete deck was designed and compared to the conventional steel reinforced concrete bridge deck design from the project AC-826579 Land Slide Repairs on PR-10 in Utuado P.R., structure BR-01 of the Puerto Rico Highway and Transportation Authority (PRHTA). The use of GRFP will allow the design to use 501 PRHTA Concrete [3] which has less corrosion resistant requirements than the PRHTA [4]. Concrete required when using steel reinforcement. The main project objective is to determine if this alternative is cost effective.

The comparison focuses on changes in deck thickness, concrete specification, and reinforcement material. This project explores the substitution of steel by GFRP [5] in a bridge deck and evaluates the associated benefits in concrete mix design, material performance, and cost reduction. By ending corrosion risk, this approach removes the need for corrosion inhibitors [6], permeability control

additives, and supplementary cementitious materials. Experimental data from trial mixes show innovative compressive strength development in early and long-term ages, while reducing costs per cubic yard. Field implementations in marine and coastal structures can confirm this solution. In particular, the recommendations of Nanni et al. (2021) [2] on sustainable and resilient concrete using non-metallic reinforcement serve as a foundational reference for this study.

The bridge deck was designed according to AASHTO LRFD [7] specifications, considering both dead and live load combinations applicable to vehicular bridges. The following design loads were used in the analysis:

- Dead Load (DL): Self-weight of the 7-inch concrete slab and GFRP reinforcement
- Live Load (LL): HL-93 loading per AASHTO LRFD [7], which includes a design truck or tandem plus lane load
- Load Factors: 1.25 for DL and 1.75 for LL under Strength I load combination

These loads were applied to a simply supported slab model spanning between AASHTO BT-65 beams spaced at 1.92 meters (center to center). See Figure 1.

Given the low modulus of elasticity of GFRP compared to steel, bridge deck design with GFRP reinforcement requires special attention to serviceability criteria, particularly crack control. Initial analytical calculations revealed that with #5 bars spaced at 4 inches and a slab thickness of 7 inches, the estimated crack width (≈ 2.71 mm) exceeded the maximum crack width limits (typically ≤ 0.7 mm) recommended by ACI 440 [8] and AASHTO LRFD [7] for bridge deck applications.

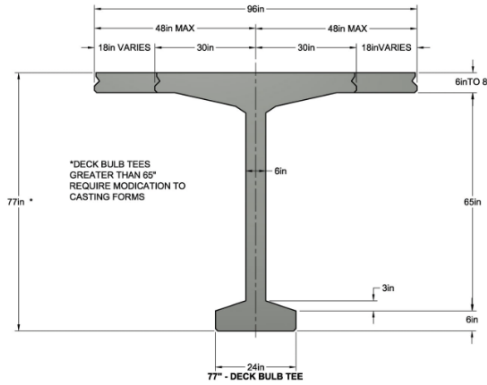


Figure 1
Deck Bulb Tee Beam Typical Detail, AASHTO/PCI,
Kniferiver Prestress

This selection of this bar was based using the data from CSA S807 MST-BAR GRADE III GFRP [5], [9] is in compliance with mechanical, physical and durability. Also, the University of Concordia performed a Bond Strength of 15 mm (#5) MST-BAR GFRP Re-Bar [5] as per ASTM D7913/D7913M. In the laboratory proved that concrete splitting controlled the failure mode, preventing full pullout capacity from being reached in the standard 200 mm cubes. Despite this, the tests showed that an 80 mm embedment length of 15 mm (#5) MST-BAR provides more than 106 kN of pullout capacity, with an average bond strength exceeding 10 MPa, meeting CSA S807-19 [9] requirements.

For this project, these findings support the confidence in specifying MST-BAR #5 GFRP reinforcement [5] for the bridge deck, even under high bond-demand conditions. However, for future evaluations consider larger-scale concrete specimens to fully assess the pullout performance of GFRP rebars and ensure conservative embedment detailing in design.

The design focuses on changes in deck thickness, concrete specification, and reinforcement material. The use of fiber-reinforced polymer bars (GFRP) in reinforced concrete structures has emerged as a sustainable and corrosion-resistant alternative to traditional steel reinforcement. This project explores the substitution of steel by GFRP in a bridge deck and evaluates the associated benefits

in concrete mix design, material performance, and cost reduction.

To address this, the design was optimized by increasing the concrete cover, using a higher-modulus GFRP bar, and implementing a double-layer reinforcement configuration #5 @ 4" Both Ways. See Figure 2.

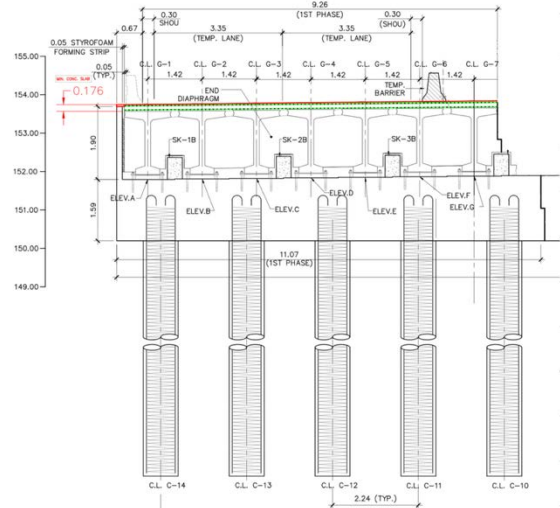


Figure 2
Section of the Bridge Shown Reinforcement GFRP Detail,
JO Virrella and Associates, AC-826579

As a result, the updated crack width was successfully reduced below 0.7 mm, meeting the serviceability criteria without compromising structural performance. Final design verification using MST-BAR #5 [5] at 4-inch spacing, with a concrete slab thickness of 7 inches and a cover of 1 inch, resulted in an estimated crack width of approximately 0.65 mm. This value satisfies the limits imposed by ACI 440.1R-15 [8] for exterior bridge decks, ensuring durability and safety under service loads. See Table 1.

Table 1
Final Design Parameters Summary

Parameter	Value
Bar Type	MTS-BAR #5
Bar Spacing	4 inches (C TO C)
Reinforcement Configuration	Double Layer (T&B)
Concrete Cover	1 inch
Slab Thickness	7 inches
Modulus of GFRP	70 GPa
Estimate Crack Width	.65 mm

However, the fundamental advantage of GFRP is its non-corrosive nature.

Unlike traditional steel reinforcement, GFRP does not rust or deteriorate in aggressive environments, including marine and de-icing salt exposure. Therefore, the traditional rationale behind strict crack width limitations to prevent chloride penetration and corrosion no longer applies in the same way.

This project addresses a critical and ongoing challenge in Puerto Rico’s infrastructure: the rapid deterioration of concrete structures in coastal areas due to corrosion of embedded steel reinforcement. By introducing GFRP, a material immune to corrosion, the proposed solution enhances the durability of bridge decks exposed to the island’s humid and saline environment. These benefits are consistent with long-term performance evaluations of GFRP conducted in harsh climates, reducing cost of concrete, less maintenance, and more resilience to the bridge decks.

Concrete Mix Trials

Segarra Engineering and Consulting in a joint venture with Concretos del Atlántico [10] and BTA Concrete [11] performed the mix designs to incorporate in this project. Two concrete specifications were evaluated to analyze their performance and compatibility with GFRP reinforcement systems: PRHTA Specification 501 [3] for Portland Cement Concrete Pavement and PRHTA Specification 934 [4] for Structural Concrete for Eastern Federal Lands projects in Puerto Rico. Both specifications target a compressive strength of 5,000 psi at 28 days but differ significantly in their composition and additive requirements. Slump [12], Temperature [13] and Air Content [14] was performed too for study purposes.

On Figure 3 shows the concrete mix design in compliance with Spec 501 – Portland Cement Concrete Pavement [3] with a target compressive strength: 5,000 psi at 28 day, the maximum slump [4] is 3 inches (fixed form), 2.5 inches (slip form), the air content [14] (if used): ≤ 6% and the allowed admixtures are water reducers [15] [16], set

retarders, superplasticizers (no calcium chloride). The aggregates have to be natural sand, coarse aggregates (2”-1”) with a minimum polishing value of 48%.

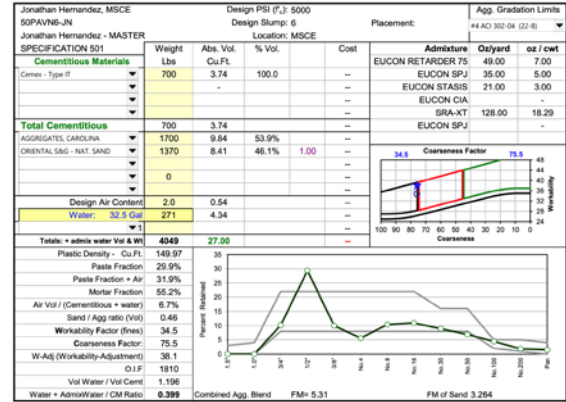


Figure 3
Concrete Mix Desing, SPEC 501, Segarra Engineering and Consulting, 2024

This is a Simpler mix design, with no requirements for corrosion inhibitors [6] or permeability testing, focusing on durability under traffic loading conditions, especially for pavements.

In the Figure 4 the concrete mix design in compliance with the Spec 934 – Structural Concrete [4] is shown. This target compressive strength is from 5,000 to 9,000 psi at 28 days depending on class. The Low permeability requirement is a max of 1,950–2,500 Coulombs as per AASHTO T-277. A maximum water-cementitious ratio of 0.30–0.50 (depending on class).

This mix use multiple chemical admixtures as required by the Spec. The admixtures are Shrinkage Reducing Admixtures (SRA) [17], Corrosion inhibitors (CI, calcium nitrite) [6], Supplementary cementitious materials (SCMs) like slag [18], silica fume, fly ash. This mix have rigorous chloride permeability control to mitigate corrosion risk in steel reinforced elements.

To better illustrate the differences between the two concrete specifications evaluated in this project, presents a comparative analysis summarizing their key technical parameters, requirements, and cost implications. This table highlights how Spec 501 [3] offers a simpler and more cost-effective solution without compromising structural performance,

making it highly compatible with non-corrosive GFRP reinforcement, while Spec 934 [4] includes numerous additives and testing requirements primarily intended to mitigate steel corrosion.

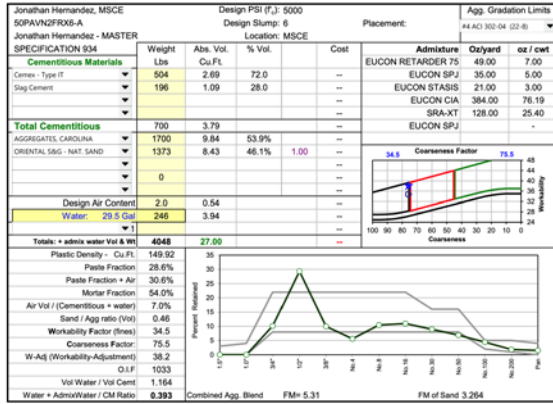


Figure 4
Concrete Mix Design, SPEC 934, Segarra Engineering and Consulting, 2024

Table 2
Comparative Analysis

Parameter	Spec 501	Spec 934
28-day Strength	5,000 PSI	5,000-9,000 PSI
Corrosion Protection	None	Corrosion inhibitor (CI) required
SCMs	Not emphasized	required (fly ash, slag, silica fume)
Permeability Test	Not required	Required, $\leq 1,950$ – $2,500$ Coulombs
Shrinkage Reduction	Not required	Required for bridge elements
Expected Cost per CuY	Lower	Higher

Since GFRP reinforcement is non-corrosive, using Spec 501[3] becomes highly advantageous. The absence of steel reinforcement eliminates the need for corrosion inhibitors [6] and permeability restrictions. Additionally, removing SCMs and costly admixtures reduces the cost of the concrete mix without compromising structural performance or durability when combined with GFRP. Trial batches prepared under both specifications shown equivalent compressive strengths, confirming that Spec 501 [3] can meet performance targets while offering a more innovative and economical solution for bridge deck applications, particularly in coastal environments where corrosion is a critical concern.

Based on these material characteristics, the design may adopt a strain-based or deformation-based serviceability approach, as supported by ACI 440.1R-15 [8] and AASHTO guidelines for GFRP-reinforced concrete. This alternative method prioritizes limiting deflection and maintaining structural integrity, rather than preventing steel corrosion via crack width control.

CONCRETE TEST RESULTS

As mentioned before in this project, Segarra Engineering and Consulting in a joint venture with Concretos del Atlántico [10] and BTA Concrete [11] collaborate to evaluate two concrete mix specifications to analyze their performance and compatibility with GFRP reinforcement: PRHTA Specification 501 [3] and PRHTA Specification 934 [4] for Eastern Federal Lands projects. Both aimed for a compressive strength of 5,000 psi at 28 days but differed significantly in additives and requirements.

The concrete trial results shown on Table 3 [19] [20] revealed that while both Spec 501 [3] and Spec 934 [4] achieved comparable compressive strengths at 28 and 56 days, their material costs diverge significantly due to the use of additives. Spec 934 [4] relies heavily on corrosion inhibitors [6], shrinkage-reducing admixtures [17], and supplementary cementitious materials (SCMs) such as slag [18] and fly ash to meet durability requirements for steel-reinforced structures. These materials, along with mandatory permeability testing, increase the cost per cubic yard by approximately 15–20% compared to Spec 501 [3].

Table 3
Test Results

Age	Control Mix (Spec 934, Psi)	Modified Mix (Spec 501, psi)	Improvement (%)
3	1870	3170	+69%
7	2990	4340	+45%
28	4890	5410	+11%
56	5530	5760	+4%

Spec 501 [3] relies on simpler, more economical mixes without corrosion inhibitors [6] or low-permeability requirements, making it highly

compatible with GFRP. In contrast, Spec 934 requires corrosion inhibitors [6], shrinkage-reducing admixtures [17], and supplementary cementitious materials, driving up cost. The trials confirmed that Spec 501 [3] achieves comparable or better strength without the complexity or cost of Spec 934 [4], supporting its use in GFRP-reinforced applications.

Cost Analysis

This analysis is based on Spec 501 [3] + GFRP costs less overall compared to Spec 934 [4] with steel despite the higher unit price of GFRP, because it eliminates the need for expensive additives and testing. In Figure 5 shows the estimate cost analysis per 30 CuY. As the Spec 934 [4] required a permeability test per AASHTO T-277 every 15 CuM or fraction the 30 CuY analysis was made to include the permeability test on the cost analysis. With these estimated costs the CuY for the 501 [3] with GFRP is \$170.00 per CuY vs \$273.33.

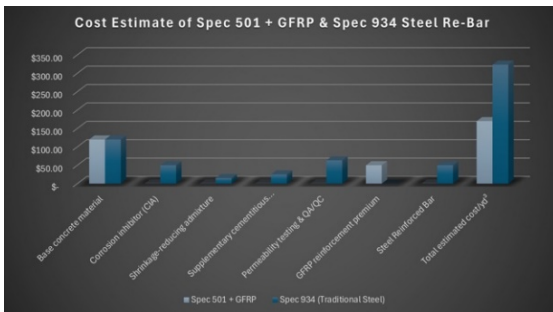


Figure 5
Estimate Cost Analysis

The bridge deck with 934 [11] Concrete and Steel Reinforced Bar with dimensions of 30 m x 9.61m x .125m is approximately 47.14 CuY. Assuming 15% of waste it will be 54.21 CuY. The cost of the Steel Rebar is approximately \$0.50 the Lb. Placing #5 bar @ 6" it will be roughly 195 #5 bar one end and 196 at the short length. With approximately 391 Bars. This, in Lbs., will be approximately 10,792 Lbs. The total cost will be \$5,396. Using GFRP with the same outcome but #5 @ 4" T&B the total of bar will be 190 in the long direction and 592 in the short direction. The total of Lbs in the deck will be 7,958 Lbs @ \$0.50 the cost will be \$3,979.00.

The total cost Using 934 [4] with steel Re-Bar will be \$14,817.22 in Concrete and 5,396.00 with Steel Re-Bar with a total of \$20,213.22. In the other hand using 501 [3] Concrete will cost \$9,215.70 + GFRP \$3,979.00 for a total of \$13,194.70.

The combined approach delivers durability, structural performance, and long-term maintenance savings. The cost advantage becomes even more pronounced over the bridge's life cycle by reducing repairs, corrosion-related damage, and downtime. In contrast, Spec 501 [3] does not require corrosion-related additives, making it inherently more economical. By combining Spec 501 [3] with GFRP reinforcement, the project achieves both structural performance and durability without the added expense of corrosion mitigation strategies, representing a major cost-saving innovation, resilience particularly for infrastructure in coastal environments like Puerto Rico.

Case Study in Bridge Projects Using GFRP

Several international bridge projects have successfully implemented cast-in-place concrete decks reinforced with GFRP rebar, offering valuable insights for applications in Puerto Rico's marine and humid environment. In Figure 6 The Millport Slough Bridge in Oregon, USA, was designed to withstand salt-laden air, humidity, and occasional flooding, confirming GFRP's excellent corrosion resistance in marine conditions.

The Montague Bridge [21] and Victoria Bridge [21] in Prince Edward Island, Canada, both located in coastal regions, demonstrated how GFRP reinforcement eliminates corrosion-related deterioration and significantly reduces maintenance in salty, humid climates.

The Bridgeport Bridge [22] in Waterloo, Ontario, though in a northern urban setting, focused on improving durability against environmental salt exposure, making it a strong reference for urban bridges exposed to aggressive environments.

Finally, in the Figure 7 the Baudette Bridge [23] in Minnesota, USA, was constructed with a focus on reducing long-term corrosion and maintenance costs from water and salt exposure. Collectively, these

projects highlight GFRP's ability to extend service life and lower maintenance costs in harsh environments similar to those found across Puerto Rico.



Figure 6

The Millport Slough Bridge in Oregon USA, GFRP Applications on Bridge Decks, Composites

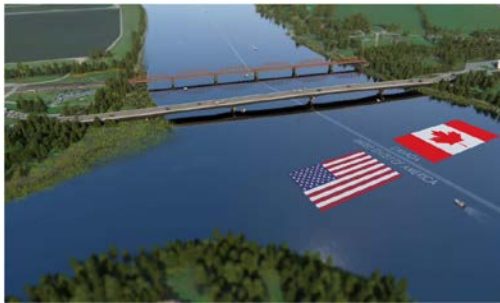


Figure 7

Boudette Bridge Min USA, GFRP Rebar Application in Bridge Decks, Composites

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

All structural verifications were conducted using Altair's S-LINE software in compliance with ACI 440.1R-15 [8] and AASHTO LRFD [7]. The reinforcement design on the bridge deck was a double-layer reinforcement layout using MST-BAR #5 [5] spaced at 4 inches top and bottom further enhances structural capacity, crack distribution, and long-term performance. This configuration aligns with successful case studies where durability and performance outweighed cosmetic crack control concerns.

The study demonstrated that an alternative deck design using GFRP and a more economical 501 PRHTA [3] concrete to the required 934 PRHTA [4] concrete required for R/C deck is cost effective for

construction and can be implemented in Puerto Rico for bridges in zones considered of higher corrosion risk as those close to marine environments.

Because the alternative deck is thicker than the original design a further study of the total bridge construction cost with GFRP deck alternative is recommended for another study as the design of other elements of the bridge could be affected by this change. If, as we believe, the cost is still more economical or competitive, it is recommended to PRHTA to implement this design as a pilot project to validate the long-term performance and cost saving that can be achieved by this technology.

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