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Environmental Impact and Life Cycle Assessment of FRP Reinforced Concrete Structures

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Work developed under the supervision of
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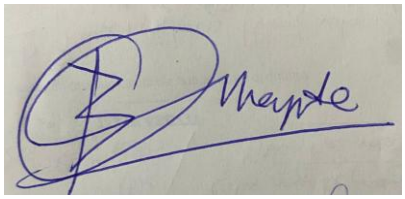

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Impatto Ambientale e Valutazione del Ciclo di Vita del Calcestruzzo Armato con FRP

RIASSUNTO

Questa tesi valuta le prestazioni in termini di carbonio incorporato dei sistemi di armatura in acciaio e in polimeri rinforzati con fibre (FRP) per ponti in calcestruzzo dalla fase di prodotto (A1–A3) alla costruzione (A4–A5) fino ai confronti basati sulla funzione e sulla vita di riferimento a 100 anni. Le evidenze sono assemblate su più scale—materiale (barre d'armatura), elementi strutturali (impalcato, pali, travi) e l'intero ponte—utilizzando coefficienti basati su EPD, quantità di progetto e metriche normalizzate rispetto alla capacità.
Emergono tre risultati coerenti. Primo, i risultati basati sulla massa favoriscono l'acciaio, mentre quelli basati sulle prestazioni favoriscono frequentemente l'FRP.
All'unità dichiarata, le barre d'acciaio mostrano un GWP A1–A3 inferiore (≈480–850 $kgCO_2e$/tonnellata) rispetto al GFRP (>2.300 $kgCO_2e$/tonnellata), e i valori per metro per barre da 10 mm sono analogamente inferiori per l'acciaio. Tuttavia, quando normalizzato rispetto alla capacità a trazione, il GFRP è più efficiente in termini di carbonio (≈$3{,}9–4{,}3\times10^{-4}$ vs $5{,}3–6{,}7\times10^{-4}$ $kgCO_2e$/MPa), riflettendo maggiore resistenza e minore densità. Secondo, le realtà della fase di costruzione contano: la bassa densità del GFRP riduce gli oneri di trasporto e può migliorare la produttività di installazione (~20%), a condizione che siano rispettati i protocolli di movimentazione e stoccaggio; l'acciaio mantiene vantaggi in termini di flessibilità in cantiere e filiere mature. Questi effetti A4–A5 riducono ma non invertono le differenze A1-A3.
Terzo, la durabilità governa gli esiti sull'intero ciclo di vita. Nel caso di studio sulla costa della Carolina del Nord, la sovrastruttura in FRP (impalcato in GFRP con travi in CFRP/GFRP) ha consentito luci maggiori (30,48 m vs 13,72 m). Normalizzando per lunghezza di campata su 100 anni, l'opzione FRP ha fornito un GWP inferiore di ≈27–36% per metro di ponte. Per i pali, il CFRP ha aumentato gli impatti A1–A3 ma ha ottenuto ~10% di GWP inferiore per metro su 100 anni grazie all'immunità alla corrosione e a una manutenzione trascurabile. Le analisi di sensibilità mostrano che i risultati dipendono dall'intensità produttiva del CFRP: ridurre il coefficiente del CFRP (28.888,8 → 14.771,3 $kgCO_2e/m^3$) migliora in modo sostanziale l'FRP sia al livello di prodotto sia sull'intero ciclo di vita.

PAROLE CHIAVE: LCA, FRP, GFRP, CFRP, Armatura in Acciaio, Potenziale di Riscaldamento Globale, Sostenibilità dei Ponti, Progettazione Senza Manutenzione

Environmental Impact and Life Cycle Assessment of FRP Reinforced Concrete Structures

ABSTRACT

This thesis evaluates the embodied-carbon performance of steel and fibre-reinforced polymer (FRP) reinforcement systems for concrete bridges from the product stage (A1–A3) through construction (A4–A5) and into function-based and 100-year reference-life comparisons. Evidence is assembled across scales—material (rebars), structural elements (deck, piles, girders), and the full bridge—using EPD-based coefficients, project quantities, and capacity-normalized metrics.

Three consistent findings emerge. First, mass-based results favour steel, while performance-based results frequently favour FRP. At the declared unit, steel rebars show lower A1–A3 GWP (≈480–850 $kgCO_2eq/ton$) than GFRP (>2,300 $kgCO_2eq/ton$), and per-meter values for 10 mm bars are similarly lower for steel. Yet, when normalized by tensile capacity, GFRP is more carbon-efficient (≈$3.9–4.3\times10^{-4}$ vs $5.3–6.7\times10^{-4}$ $kgCO_2eq/MPa$), reflecting higher strength and lower density. Second, construction-stage realities matter: GFRP's low density reduces transport burdens and can improve installation productivity (~20%), provided handling and storage protocols are observed; steel retains advantages in on-site flexibility and mature supply chains. These A4–A5 effects narrow but do not reverse A1–A3 differences.

Third, durability governs whole-life outcomes. In the coastal North Carolina case study, the FRP superstructure (GFRP deck with CFRP/GFRP girders) enabled longer spans (30.48 m vs 13.72 m). Normalizing by span length over 100 years, the FRP option delivered ≈27–36% lower GWP per metre of bridge. For piles, CFRP raised A1–A3 impacts but achieved ~10% lower GWP per metre over 100 years due to corrosion immunity and negligible maintenance. Sensitivity analyses show results hinge on CFRP manufacturing intensity: reducing the CFRP coefficient (28,888.8 → 14,771.3 $kgCO_2eq/m^3$) materially improves FRP at both product and whole-life levels.

KEYWORDS: LCA, FRP, GFRP, CFRP, Steel Reinforcement, Global Warming Potential, Bridge Sustainability, Marine Structures.

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

ADPf	Abiotic Depletion Potential-fossil
ACI	American Concrete Institute
AP	Acidification Potential
BOF	Basic Oxygen Furnace
CEN	European Committee for Standardization
CFRP	Carbon Fibre Reinforced Polymer
CRSI	Concrete Reinforcement Steel Institute
CNR	Advisory Committee on Technical Recommendations for Construction
CO_2	Carbon Dioxide
EAF	Electric Arc Furnace
EP	Eutrophication Potential
FRP	Fibre Reinforced Polymer
GHG	Green House Gas
GFRP	Glass Fibre Reinforced Polymer
GPR	Ground Penetrating Radar
GWP	Global Warming Potential
LCA	Lifecycle Assessment
PAN	Polyacrylonitrile
PCR	Product Category Rules
PI	Principal Investigator
RSL	Reference Service Life
SDGs	Sustainable Development Goals

Symbols

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1. INTRODUCTION

The construction industry, a cornerstone of global infrastructure development and contributor to roughly 13% of global GDP, is simultaneously a leading driver of environmental degradation [1]. It accounts for approximately 39% of total global greenhouse gas (GHG) emissions, of which 11% stem from embodied carbon emissions linked to material extraction, processing, transportation, and construction activities [2]. A central material within this sector is reinforced concrete (RC), valued for its structural versatility, high compressive strength, and cost-efficiency, making it the most widely used construction material worldwide. However, the conventional use of steel reinforcement in RC presents significant environmental challenges.

Steel production is highly energy-intensive and emits approximately 1.85 metric tons of CO_2 per ton of steel produced [3]. Moreover, cement production alone contributes nearly 8% of global CO_2 emissions, further compounding the environmental footprint of RC structures [4]. In addition to its carbon intensity, steel reinforcement is prone to corrosion, which compromises the durability and longevity of concrete structures, leading to increased maintenance demands and resource consumption [5]. These issues underscore the urgent need for sustainable alternatives in reinforcement technologies.

In parallel with the global transition toward low-carbon economies, there is increased emphasis on assessing and reducing the environmental impacts of infrastructure projects over their life cycles. This has driven the adoption of Life Cycle Assessment methodologies, the rise of Environmental Product Declarations, and the emergence of low-carbon procurement frameworks like the Buy Clean Initiative in the United States and EN 15804 in the European Union. Public infrastructure agencies are now actively integrating these frameworks into material selection and policy mandates.

The growing need for eco-efficient infrastructure is intensifying the demand for advanced materials that meet both performance and sustainability criteria. Urbanization, climate change, and the depletion of non-renewable resources have forced stakeholders in the construction sector to reconsider material choices. Governments and international organizations are increasingly instituting green building codes and regulations that reward low-impact materials and life cycle transparency.

In response, the use of Fibre-Reinforced Polymer (FRP) materials — particularly Glass Fibre-Reinforced Polymer (GFRP) and Carbon Fibre-Reinforced Polymer (CFRP) — has emerged as a viable and increasingly adopted alternative to traditional steel reinforcement. These materials promise corrosion resistance, durability, and a reduced environmental footprint, offering considerable potential for sustainable and resilient infrastructure [6].

FRPs, especially GFRP, offer advantages such as low weight, corrosion resistance, electromagnetic neutrality, and a longer service life under harsh environmental conditions. These properties make GFRP especially suitable for infrastructure exposed to aggressive agents such as chlorides, moisture, or freeze-thaw cycles [7], [8]. CFRP, while more expensive, offers superior tensile strength and stiffness, making it ideal for high-performance structural applications, especially where prestressing is required [9].

The integration of FRPs into reinforced concrete structures not only addresses durability concerns but also contributes toward achieving sustainable development goals (SDGs) related to climate action, industry innovation, and infrastructure resilience [10].Steel remains the most widely used reinforcement material due to its availability, cost-effectiveness, and mechanical performance. However, its inherent vulnerability to corrosion leads to premature deterioration of reinforced concrete structures, particularly in marine environments, bridge decks, and deicing salt-exposed regions [5]. An industry study reviewing lifecycle costs in concrete infrastructure—such as bridges and parking structures—found that 50% of corrosion repairs fail within just 10 years, meaning half the structures required repeat intervention within a decade [11].

Corrosion of steel leads to concrete spalling, structural capacity reduction, and increased maintenance costs. From an environmental perspective, steel production is energy-intensive and contributes significantly to CO_2 emissions, owing to the combustion of fossil fuels and the reduction of iron ore in blast furnaces. Moreover, mining and raw material extraction required for steel production particularly refractories and alloying elements can result in habitat destruction, water contamination, and high resource depletion.
These drawbacks provide compelling motivation to explore corrosion-resistant and lower-impact alternatives like GFRP and CFRP, especially for infrastructure expected to endure for more than 75–100 years with minimal intervention [12].

GFRP and CFRP rebars are typically composed of high-strength glass or carbon fibres embedded in a polymeric resin matrix, offering a high strength-to-weight ratio and excellent durability. GFRP has become prominent in industries such as civil engineering, marine infrastructure, and wind energy, while CFRP has found applications in aerospace, automotive, and now increasingly, high-performance civil structures.

Lifecycle studies confirm that replacing steel with FRP in reinforced concrete structures can substantially improve environmental metrics, especially when evaluated over the entire service life. This supports their growing role in sustainable design strategies, especially in coastal, industrial, or high-humidity zones. When comparing GFRP and CFRP to steel reinforcement, several mechanical and durability-based distinctions become evident. Steel rebars exhibit a high tensile modulus (~200 GPa), providing superior stiffness and load-bearing capacity [13]. However, they are highly susceptible to corrosion, especially when exposed to chlorides, acids, or moisture ingress, leading to significant structural deterioration and costly maintenance cycles.

By contrast, GFRP rebars typically demonstrate a tensile modulus between 40 and 60 Gpa [13]. While this is lower than steel, their high tensile strength, non-corrosive nature, and lower density make them attractive for environments where long-term durability and reduced structural weight are priorities. CFRP rebars go even further, offering tensile strengths up to three times that of steel and very high stiffness (up to 150–200 GPa), which allows them to replace steel in high-performance or prestressed elements.

Utilization of both GFRP and CFRP in construction, allows for thinner structural sections, weight reduction, and material savings [7], [14]. Life Cycle Assessment (LCA) is an increasingly adopted tool in evaluating the environmental footprint of construction materials. LCA studies assess the environmental impacts of materials across their lifecycle stages — from raw material extraction, manufacturing, and transport to use, maintenance, and end-of-life treatment.

1.1.Background

Environmental Product Declarations (EPDs) serve as a key instrument for assessing and reporting the environmental impacts of construction materials. In the United States, interest in EPDs has grown significantly following the launch of the Federal Buy Clean Initiative. For instance, as of March 2022, the U.S. General Services Administration (GSA) mandated that suppliers submit Type III EPDs for concrete and asphalt used in federal construction projects involving more than a single truckload. With this federal requirement in place, it is anticipated that similar obligations will soon extend to state-level procurement and private-sector developments.

EPDs are created and published in accordance with Product Category Rules (PCRs), which define the detailed procedures, requirements, and methodological guidelines for preparing EPDs for specific product groups. The PCR establishes the framework for conducting the underlying Life Cycle Assessment (LCA). As illustrated in Figure 1.1, a full LCA encompasses multiple life cycle stages, all of which must be considered to generate a comprehensive EPD.

At a minimum, EPDs must cover the product stage—designated as Modules A1 through A3 in Figure 1.1—a scope commonly referred to as "Cradle-to-Gate." Some declarations go further, labeled as "Cradle-to-Gate with options," and also include additional life cycle phases such as A4–A5 (construction process) or B1–B7 (use phase), depending on the parameters modeled in the LCA.

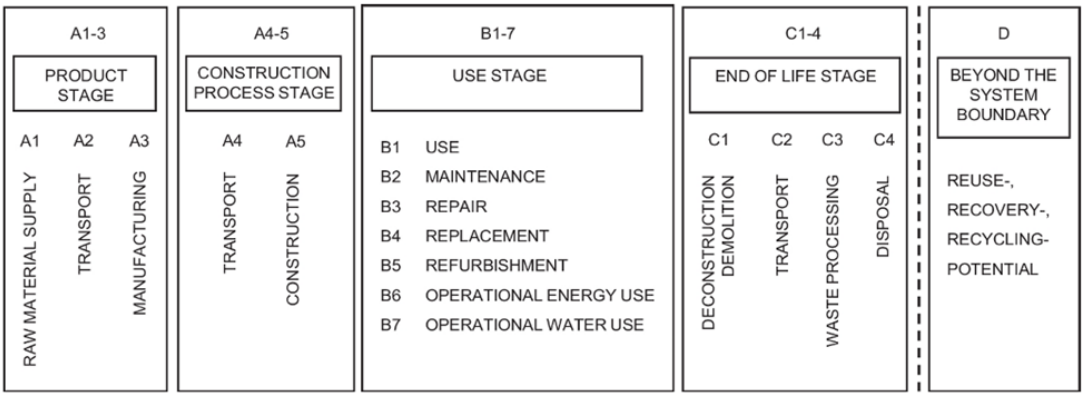


Figure 1.1: Modules of the life cycle of a building element from EN 15804 (2019)

In September 2022, the Concrete Reinforcing Steel Institute (CRSI) released an industry-wide Environmental Product Declaration (EPD), certified by ASTM International under Declaration

Number 362 [34]. This declaration—ASTM-EPD362—applies to fabricated steel reinforcing bars (rebars) intended for use in both concrete and masonry construction. The EPD follows the guidelines established in Part A of the Product Category Rules for Building-Related Products and Services, as published by UL Environment in 2018.

The scope of the declaration encompasses steel reinforcement that is produced in U.S. mills and subsequently fabricated (cut, bent, or otherwise shaped) to meet specific project requirements, as defined by standards CSA G30.18, ASTM A615, and ASTM A706. CRSI also maintains a comprehensive list of participating mills and fabricators throughout North America whose data contributed to the development of this EPD and who are authorized to use it to meet project documentation needs.

ASTM-EPD362 is categorized as a "Cradle-to-Gate" declaration, covering the Product Stage modules illustrated in Figure 1.2. It represents a North American industry average for the production of fabricated steel rebar during the 2020 reference year. The EPD specifies a declared unit of 1 metric ton of fabricated steel reinforcing bar, with a material density of 7850 kg/m³.

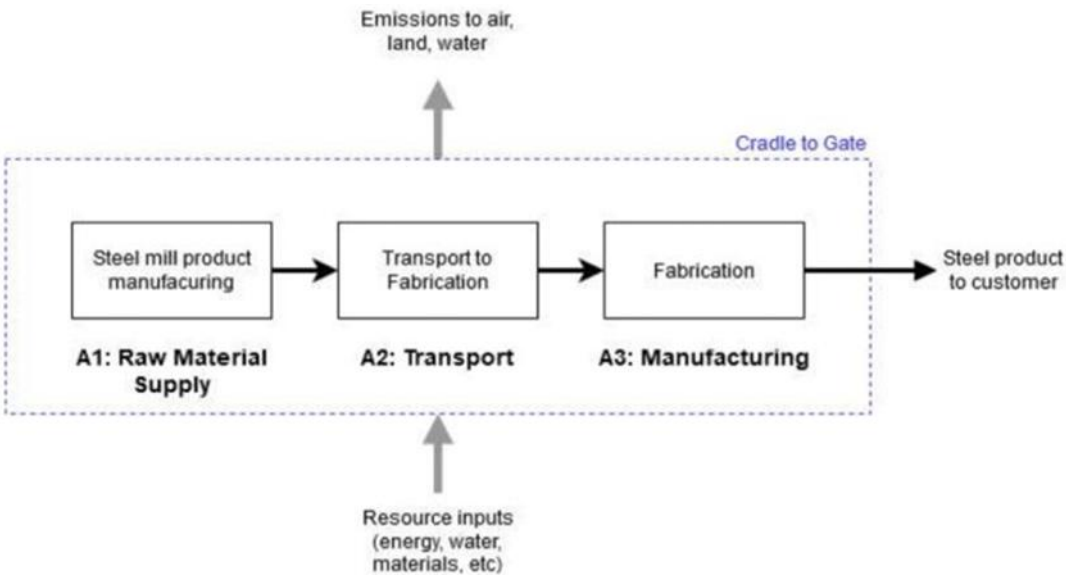


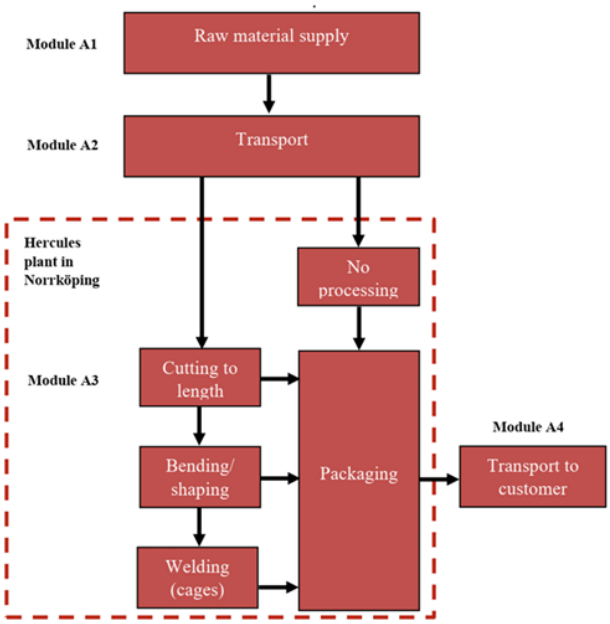
Figure 1.2: Cradle-to-Gate product flow diagram from CRSI [34].

On an international level, there are several “Cradle-to-Gate with options” Environmental Product Declarations (EPDs) available for steel reinforcement products. A notable example is the Hercules Armering EPD, which has been certified by the International EPD System based

in Sweden. Hercules Armering operates as a distributor of steel reinforcement mesh and customized prefabricated rebar cages. In this EPD, the product system is illustrated through a process flow diagram (Figure 1.3), which accounts for downstream transportation from the production facility (the "Gate") to the customer—captured as Module A4. For this module, the EPD includes scenario-based transportation details derived from weighted average logistics data, as outlined in Figure 1.3b.

Additionally, Waldman et al [35] published a comprehensive report cataloging all known North American EPDs, offering a consistent benchmark for comparing the embodied carbon of building materials, specifically for Modules A1 through A3 (Cradle-to-Gate). In the context of ready-mix concrete, the report provides both regional and national baseline Global Warming Potential (GWP) values—expressed in kilograms of CO_2-equivalent per cubic meter—relative to different compressive strength classes.

Among the materials included in the North American Material Baseline database is fabricated reinforcing steel, which is reported to have an industry-wide GWP of 854 kg CO_2-eq per metric ton. This value aligns precisely with that reported in ASTM-EPD362 [34]. However, one notable omission in this database is the absence of EPD data for pultruded glass fiber-reinforced polymer (GFRP) bars used in reinforced concrete applications. This gap highlights the need for further research—serving as a primary impetus for the present study.



Parameter	Unit (per declared unit)	Value
Vehicle type used for transport	-	Truck for regional transport, Euro 6
Vehicle load capacity	tonne	Payload capacity 28-40 tonnes
Fuel type and consumption	Litre of fuel type per distance	Diesel (6.4% biobased assumed), about 4 liters per 10 km
Distance to central warehouse or storage, if relevant	km	Not relevant
Distance to construction site	km	384
Capacity utilization	%	81
Bulk density of transported products	kg/m^3	7 800
Volume capacity utilization factor (factor: = 1 or < 1 or ≥ 1 for compressed or nested packaged products)	Not applicable	-

Figure 1.3 a: Product process flow(A1-A3) (b) scenario based weighted average details

1.2. Motivation of Research

The adoption of GFRP reinforcement in concrete structures is anticipated to increase across the United States. Standards for both material properties (ASTM D7957) and construction practices [15], [16] (ACI 440.5) are already established, and the recent publication of the ACI 440.11 (2022) building code—which was approved in the latest International Building Code (IBC) cycle—further solidifies its regulatory framework. In order for GFRP to remain a viable and competitive alternative to traditional steel reinforcement, particularly as a more durable option, the industry must now prioritize the development of Environmental Product Declarations (EPDs).

To support this effort, the American Composites Manufacturers Association (ACMA) has commissioned NSF International to create a Product Category Rule (PCR) for composite products. This initiative specifically targets solid round pultruded GFRP rebars that comply with ASTM D7957. A dedicated PCR Committee, is currently steering the development

process. The committee's immediate focus lies on addressing Modules A1–A3 (as shown in Figure 1.1), which are essential for Cradle-to-Gate EPD reporting.

However, many of GFRP's key advantages over steel become evident beyond the product stage—particularly during the Construction Process Stage (Modules A4–A5) and the Use Stage (Modules B1–B5). Additionally, GFRP's relatively low transverse shear strength provides benefits during deconstruction or demolition, categorized under the End-of-Life Stage (Module C1). While GFRP manufacturers currently possess sufficient data to evaluate the GWP for Modules A1–A3, there is a noticeable lack of comprehensive analysis regarding the environmental implications once the product exits the factory gate.

To date, only limited research has explored these downstream phases. One such example is a case study by [15], [16], which documents the construction of a 186-foot-long GFRP-reinforced concrete bridge in Florida. While informative, this case represents a relatively small-scale application, and further studies are required, especially to better understand transportation logistics and handling characteristics compared to steel reinforcement. Likewise, a broader assessment of durability has been presented in a report by Benzecry et al [36], which examined GFRP rebars retrieved from bridges that had been in service for 15 to 20 years.

Despite these valuable contributions, significant uncertainty remains regarding how best to quantify the performance differences between GFRP and steel reinforcement during the Use Stage (Modules B1–B7), particularly in defining an appropriate Reference Service Life (RSL) for lifecycle modeling and impact evaluation.

1.3.Objectives

- To calculate the (GWP) [kg CO2 eq.] of Steel and GFRP reinforcing rebars, according to an appropriate Declared Unit corresponding to the Cradle-to-Gate (Modules A1-A3) product flow

- To develop scenario-based parameters and declared units to quantify the GWP of GFRP reinforcing bars beyond (Modules A1-A3)

- Assess FRP- Global Warming Potential perfomance at the Structural level

1.4.Structure of Thesis

This thesis is structured as follows:

Chapter 1: Introduction — Provides the research background, motivation, and scope.
Chapter 2: State of the art — Surveys technical and environmental studies on GFRP, CFRP, and steel, including case studies and LCA data.
Chapter 3: Methodology — Details the LCA framework, system boundaries, data sources,volumes and comparison methods.
:Results and Discussion— Presents the environmental impacts of reinforcement systems across bridge components and interprets results, limitations, and implications for policy and practice.
Chapter 4: Conclusion — Summarizes findings and outlines future research directions.

2. STATE OF THE ART

This chapter provides a comprehensive review of the scientific, technical, and environmental literature concerning the use of steel, GFRP, and CFRP reinforcements in concrete structures—particularly in the context of infrastructure projects such as bridges. The review explores key themes surrounding the environmental impact of construction materials, with emphasis on embodied carbon LCA, EPDs, and performance-based case studies of reinforced concrete applications.

The purpose of this chapter is threefold:

- To establish the technical context for selecting and applying alternative reinforcements in reinforced concrete, especially in aggressive environments such as marine and de-icing salt-exposed regions.
- To review existing LCA studies and EPD data on metallic and fiber-reinforced polymers to support a scientifically grounded comparison of their environmental burdens.
- To identify methodological challenges and gaps in the application of LCA and EPD frameworks for novel materials such as FRPs, which remain underrepresented in regulatory databases and harmonized standards.

The chapter is organized thematically, starting with the fundamentals of reinforced concrete in infrastructure, followed by sections on material-specific characteristics, lifecycle environmental performance, and integration of case studies. Emphasis is placed on cradle-to-gate impacts (modules A1–A3) in accordance with EN 15804 and ISO 14040/44 standards, which form the basis for EPD-based analysis used in the research.

2.1. Introduction to Reinforced Concrete in Infrastructure

Global Use of Reinforced Concrete

Reinforced concrete (RC) remains the dominant structural material used worldwide in civil infrastructure projects, including bridges, marine piers, highway overpasses, and high-rise buildings. Its advantages, compressive strength, design flexibility, cost-effectiveness, and material availability—have made it indispensable in both developed and developing countries

[17]. However, to perform under tensile stress, concrete must be reinforced with materials that can resist tensile forces and mitigate cracking.

Steel rebar, with its excellent tensile strength and compatibility with concrete's thermal expansion, has historically fulfilled this role. Globally, over 1.8 billion metric tons of cement were consumed in 2022 alone [18], the vast majority of which supported RC construction.

Durability and Corrosion Challenges

Despite its structural performance, traditional carbon steel rebar has one major vulnerability: corrosion. In marine environments or areas exposed to road salts, deicing chemicals, and aggressive groundwater, chloride ingress and carbonation lead to de-passivation of the protective oxide layer on steel, triggering corrosion [5]. Corrosion causes spalling, cracking, and ultimately, structural degradation that requires costly and frequent maintenance.

Studies indicate that corrosion of embedded steel is responsible for the majority of maintenance costs in concrete infrastructure, especially in bridge decks and piles [12]. In the United States alone, the estimated cost of corrosion in infrastructure exceeds $22 billion annually. These challenges have driven the exploration of alternative reinforcements with better chemical resistance and lower lifecycle maintenance demands.

Why GFRP Composite Reinforcement?

As engineers increasingly seek to deliver more sustainable, safe, and durable concrete structures, (GFRP) reinforcement is being adopted in innovative applications across a wide range of bridge decks and structural components. A key motivation for this shift is the vulnerability of traditional steel reinforcement to corrosion, as illustrated in Figure 2.1, which shows typical deterioration in steel-reinforced concrete (RC) bridge structures.

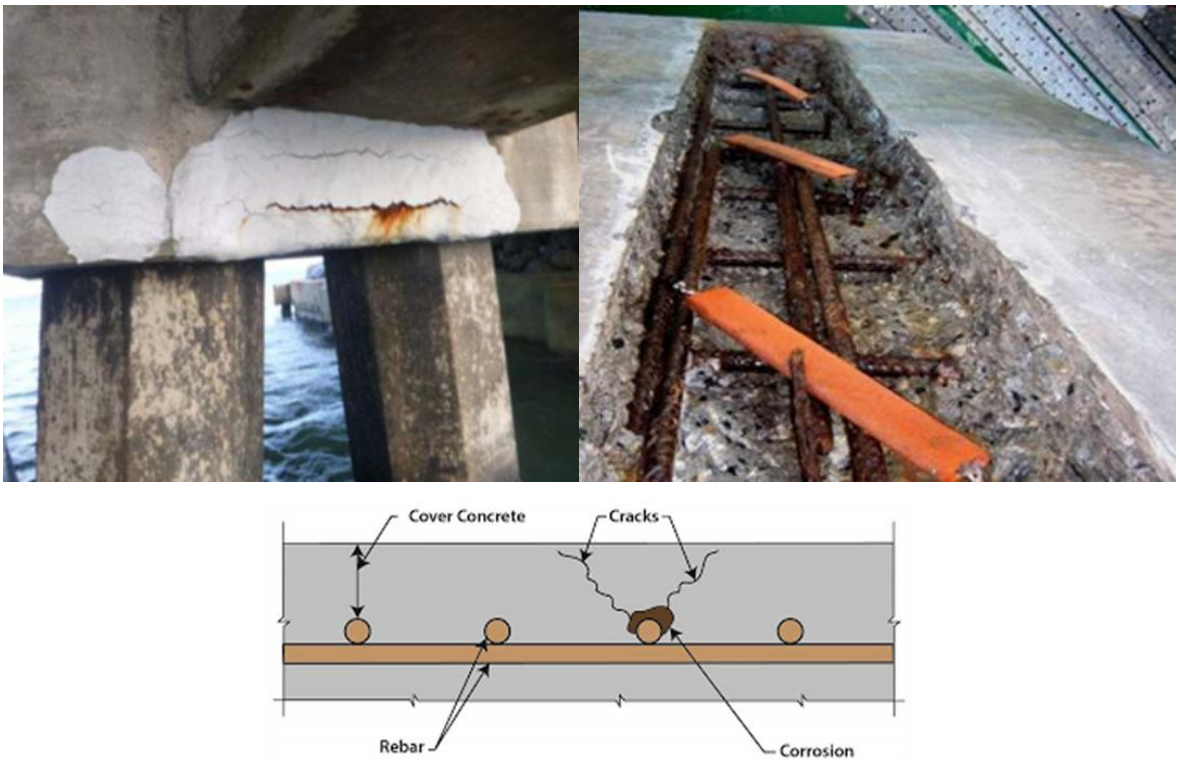


Figure 2.1: Typical Corrosion in Steel RC Bridge Structures

Overview of FRP Composite Reinforcement

With GFRP reinforcement already proven in hundreds of successful infrastructure projects, its applications are now extending to larger and more complex structures. Typical uses include both new construction and rehabilitation of bridge components such as decks, barriers, approach slabs, and sidewalks, as well as precast elements including bridge decks, box girders, and curbs. This versatility is illustrated in Figure 2.2, which highlights the wide range of bridge elements—girders, decks, piles, and columns—where FRP reinforcement has been effectively applied.

(a)FRP in Girders

(b)FRP in Bridge Decks

c)FRP in Piles and Columns

Figure 2.2: Use of FRP Reinforcement in Bridge Elements

Influence of Codes and Specifications on Material Selection

Modern bridge design is increasingly guided not only by load-bearing requirements but also by durability-based approaches and service life modeling. To address long-term performance, agencies such as AASHTO, CSA (Canada), and fib (International Federation for Structural Concrete) have incorporated provisions for non-metallic reinforcement, particularly in bridge decks and piles exposed to aggressive environments. Within this context, GFRP has gained significant traction in regions such as North America and the Middle East, where design codes including ACI 440.1R-15 and CSA S806 formally permit its use in selected bridge elements. Meanwhile, CFRP—despite its higher cost—has been adopted in prestressed applications such as strands, owing to its superior strength-to-weight ratio and fatigue resistance [19]. These code and specification developments directly underpin the relevance of this study, which evaluates GFRP and CFRP systems in comparison with conventional steel reinforcement. Figure 2.3 illustrates examples of codes and specifications that contain explicit provisions for FRP reinforcement.

Figure 2.3: Example Codes and Specifications with provisions for FRP

2.2.Life Cycle Assessment (LCA) in Infrastructure

Fundamentals and Purpose of LCA

(LCA) is a standardized methodology for assessing the environmental performance of products across their life cycles, including raw material extraction, manufacturing, use, and disposal (ISO 14040:2006; ISO 14044:2006). In the context of construction, LCA helps compare different materials or design options based on environmental impact categories, such as:

- Global Warming Potential (GWP): Expressed in kg CO_2 eq, as a measure of climate change impact.
- Abiotic Depletion Potential – Fossil (ADPf): Measured in MJ, reflecting fossil fuel resource depletion.
- Acidification Potential (AP): kg SO_2 eq, associated with acid rain formation.
- Eutrophication Potential (EP): kg PO_4^{3-}e, linked to nutrient enrichment of aquatic systems.
- Photochemical Ozone Creation Potential (POCP): kg ethene eq., linked to smog formation.

Among these, GWP is emphasized in this thesis.

These impacts are assessed based on a functional unit (e.g., 1 m^3 of reinforced concrete), ensuring comparability across alternatives.

Modular Approach in LCA (A1–C4, D)

When LCA is used for construction materials, the analysis typically adopts the modular structure defined by EN 15804, including stages such as:

- A1–A3: Raw material supply, transport, and manufacturing (cradle-to-gate),
- A4–A5: Transport to site and installation,
- B1–B7: Use stage (maintenance, operation, etc.),
- C1–C4: End-of-life (demolition, disposal, etc.).
- D: Benefits beyond the grave

Most EPDs for construction materials today report only modules A1–A3, making them suitable for cradle-to-gate analysis but limiting full lifecycle comparison. The growing adoption of (EPDs)—third-party verified documents that present LCA results—is enabling more transparent and consistent environmental comparisons [20]. However, variability in Product Category Rules (PCRs), system boundaries, and assumptions make direct comparisons between different materials, especially FRPs and steel, technically challenging [21].

Tools and Databases Used in LCA

Popular software tools such as SimaPro, GaBi, and OpenLCA are used to perform LCA modeling, drawing from databases such as Ecoinvent, USLCI, and GaBi Thinkstep. While these tools offer powerful analytical capabilities, they require careful modeling to align assumptions and data sources when comparing novel materials like GFRP or CFRP to well-documented materials like steel.

In this thesis, the LCA comparisons draw directly from published EPDs, manufacturer PCRs, and secondary studies using software-based LCA simulations.

2.3. Environmental Product Declarations (EPDs) and Product Category Rules (PCRs)

EPDs are third-party verified LCA documents developed in accordance with PCRs (Product Category Rules). They standardize how environmental data is reported, allowing procurement officials, engineers, and designers to assess and compare environmental burdens[22].
However, EPDs are not always directly comparable due to differences in:

- Functional units (e.g., per kg of material vs per meter of bar),
- System boundaries,
- Data quality and geographic specificity (regional electricity grids, transport modes), and
- Allocation procedures.

For FRP materials, particularly CFRP, the lack of harmonized PCRs and industry-wide datasets introduces variability that can affect LCA-based material decisions.

The Role of EPDs and PCRs in Material Comparison

EPDs follow a common format governed by Product Category Rules (PCRs), which specify how the LCA must be conducted for a certain type of product (e.g., construction products). For reinforcement bars and fibres, the relevant PCRs often follow ISO 21930 or EN 15804+A2. However, some EPDs for FRPs rely on manufacturer-specific data or national databases (e.g., GaBi, SimaPro) without harmonized functional units.
Moreover, GFRP and CFRP manufacturing processes differ significantly from steel: FRPs are produced via pultrusion or filament winding with energy-intensive resin curing, whereas steel is produced via electric arc furnaces or basic oxygen furnaces. These process differences must be accounted for through normalization, functional equivalency, and system expansion, all of which are methodological challenges within LCA.

2.4. Materials for Reinforcement: Overview and Comparison

Steel Reinforcement: Properties and Limitations

Steel is the most established reinforcement material in concrete, valued for its high tensile strength, ductility, predictable performance under stress, and widespread acceptance in

structural codes. Industrially, it is produced primarily through Basic Oxygen Furnace or Electric Arc Furnace processes. However, despite its mechanical advantages, steel production carries significant environmental burdens due to high energy consumption, raw material extraction, and associated greenhouse gas emissions.

Table 2.1 summarizes the key mechanical properties of steel reinforcement, while Table 2.2 outlines its advantages and limitations in structural applications.

- **Mechanical Properties:**

Table 2.1: Steel Mechanical Properties

Property	Typical Values
Tensile strength	400–600 MPa
Modulus of elasticity	~200 GPa
Ductile	
Excellent bond with concrete	

- **Environmental Profile:**

According to multiple EPDs (e.g., Nucor, CMC, CSRI, DEACERO, Hercules):

Global Warming Potential (A1–A3): 0.75–1.10 kgCO_2eq per kg of steel

Abiotic Depletion (Fossil): 1.2–1.5 MJ/kg

Steel production via EAF uses scrap (~90%), reducing energy consumption and emissions

Corrosion requires protective coatings (epoxy, galvanized), increasing environmental burden

Table 2.2: Steel Pros and Cons

Advantages:	Limitations:
High Strength, Ductility, and Predictable Performance	Corrosion susceptibility shortens service life in marine or chloride environments
Strong Bond Compatibility with Concrete (has a thermal coefficient similar to concrete)	High maintenance and replacement costs
Wide Availability, Recyclability, and Cost Efficiency	Heavy weight increases transportation emissions (A4), and also other efforts, such as handling on site with personnel or equipment

Glass Fiber Reinforced Polymer (GFRP): Composition and Use

GFRP bars are composed of continuous glass fibers embedded in a thermoset resin matrix, typically vinyl ester or epoxy, and are most commonly manufactured using the pultrusion process. Their lightweight nature and inherent resistance to corrosion make them particularly suited for applications in aggressive environments such as bridge decks, marine infrastructure, and water treatment facilities.

Table 2.3 presents the key mechanical properties of GFRP reinforcement, while Table 2.4 outlines its advantages and limitations compared to conventional steel reinforcement.

- **Mechanical Properties:**

Table 2.3:GFRP Mechanical properties

Property	Typical Values
Tensile strength	600–1,200 MPa
Modulus of elasticity	40–60 GPa (significantly lower than steel)
Lightweight (1/4 the density of steel)	2100 kg/m^3
Anisotropic behavior requires special design considerations	

- **Environmental Profile:**

From EPDs such as VROD, MateenBar, Dextra, Solidian, and ATP:

GWP (A1–A3): 1.5–2.3 kg CO_2eq/kg (higher than steel per kg, but lower per strength unit)

Abiotic Depletion (Fossil): 40–80 MJ/kg (due to resin production)

Significantly lower emissions over full life cycle due to no corrosion and longer service life

Transport impacts (A4) are substantially reduced due to lower weight and other efforts, such as handling on site with personnel or equipment.

Table 2.4: Pros and Cons of GFRP

Advantages:	Limitations:
Zero corrosion—ideal for aggressive environments	Higher upfront material cost per kg
Excellent durability and longevity (>100 years in well-designed applications)	Lower modulus requires increased bar area in flexural applications
Reduced maintenance and lifecycle costs	Design codes still evolving for widespread adoption

Carbon Fiber Reinforced Polymer (CFRP): Characteristics and Applications

CFRP reinforcement is composed of high-strength carbon fibers embedded in a polymer matrix. Among all reinforcement materials, it provides the highest tensile strength and stiffness, making it particularly advantageous for demanding applications. Due to its superior mechanical properties, CFRP is especially well-suited for prestressing uses such as bridge girders, precast piles, and other structural components requiring long-term durability and minimal deformation.

Table 2.5 presents the mechanical properties of CFRP reinforcement, while Table 2.6 outlines its primary advantages and limitations relative to conventional alternatives.

- **Mechanical Properties:**

Table 2.5: CFRP Mechanical Properties

Property	Typical Values
Tensile strength	1,200–2,000 MPa
Modulus of elasticity	150–200 GPa (comparable to steel)
Lightweight and fatigue-resistant	2100 kg/m^3
Electrically conductive (unlike GFRP)	

- **Environmental Profile:**

Based on peer-reviewed LCAs[23], [24]:

GWP (A1–A3): 12–31 kgCO_2eq/kg

ADPf: >200 MJ/kg

High energy consumption in carbon fiber production (especially PAN-based fibers)

Low mass per strength delivered

Table 2.6: CFRP Pros and Cons

Advantages:	**Limitations:**
Unmatched performance for prestressing and fatigue-critical structures	Very high production cost and embodied carbon per kg
No corrosion; suitable for harsh marine or seismic zones	Limited commercial availability and design code coverage
An extended life cycle justifies high impact at cradle-to-gate	Less favorable sustainability metrics unless used in long-term or highly corrosive environments

Comparison of Steel, GFRP, and CFRP in Concrete Infrastructure:

This section synthesizes and compares published LCAs and verified EPDs for steel, GFRP, and CFRP reinforcements in reinforced concrete applications. It focuses on the cradle-to-gate impacts (A1–A3) for each material and discusses implications for embodied carbon performance in structural elements like decks, piles, and girders.

i)Impact Categories Used in LCA

The key environmental impact categories assessed in this study align with those prescribed in EN 15804 and ISO 14040/44. These include GWP, ADPf, AP, EP, POCP. Among these, GWP and ADPf are most commonly reported in EPDs, and GWP is the one emphasized in this thesis.

ii)Cradle-to-Gate Comparisons from EPDs

To compare GWP values, multiple EPDs were analyzed and summarized in Table 2.7:

Table 2.7: GWP Comparison (Steel vs FRP)

Material	Source EPD	GWP ($kgCO_2eq/kg$)
Steel (EAF)	Nucor (USA)	0.36
Steel (EAF)	Dongkuk (China)	1.34
GFRP	VROD (Canada)	3.09
GFRP	Dextra (Thailand)	2.37
GFRP	Solidian (Croatia)	2.71
CFRP	[23], [24]	12-31

Note: Values normalized per kg of product irrespective of specific diameter. In application, impacts are scaled by required reinforcement volume for design strength.

iii)Functional Unit-Based Comparison in Concrete Elements

To account for performance equivalence, several studies use a functional unit of 1 m^3 of reinforced concrete, adjusting for reinforcement ratios and mechanical properties [8], [25], [19], [24].

iv)Case-Specific Factors Affecting Comparability

Several important technical and methodological factors affect LCA comparison including:
Design efficiency: FRPs may require increased bar spacing or size due to lower modulus [26]. Coatings and corrosion protection for steel increase its A1–A3 impacts but are often omitted in basic steel EPDs. Geographic factors: Electricity mix in resin or steel production significantly affects GWP [27]. Transportation impacts (A4): Can favor GFRP and CFRP due to lower weight per unit of performance [28].

2.5. Procurement and Sustainability Considerations

The Role of Procurement in Sustainable Construction

Procurement is a vital organizational function that involves obtaining goods, services, and infrastructure from external sources. It plays a key role in supply chain operations by ensuring the timely acquisition of essential resources to meet strategic and operational goals. This complex function spans a wide range of activities, including strategic sourcing, contract negotiation and management, supplier engagement, and risk mitigation. Sustainable procurement refers to the practice of acquiring goods, services, and infrastructure in ways that minimize negative environmental, social, and economic impacts. This approach takes into

account the entire life cycle of a product or service—from the extraction of raw materials through to disposal or recycling [25].

Sustainable procurement is increasingly important for several reasons. Firstly, it helps organizations reduce their environmental footprint by sourcing eco-friendly products and services, thereby cutting emissions, water use, and waste. Secondly, it supports social responsibility by encouraging partnerships with suppliers that uphold fair labor practices and human rights, contributing to a more equitable society. Thirdly, from an economic standpoint, sustainable procurement can enhance long-term financial performance by lowering operational costs and improving corporate reputation.

Benefits of Implementing Sustainable Procurement Strategies

Sustainable procurement offers a wide range of advantages across environmental, social, and economic dimensions [3]. These benefits include:

Minimized Environmental Impact: By adopting sustainable procurement approaches, organizations can significantly reduce their environmental footprint. This includes cutting down on greenhouse gas emissions, limiting waste and pollutants, and conserving finite natural resources through responsible sourcing of products and services.

Positive Social Outcomes: Procurement sustainability extends to evaluating the social conditions under which goods and services are produced. It prioritizes ethical labor practices, the protection of workers' rights, and the promotion of health and safety standards [29]. Furthermore, it supports diversity, equity, and inclusion initiatives, strengthens local economies, and discourages the use of hazardous materials.

Stronger Economic Performance: Integrating sustainability into procurement strategies can yield financial gains. Organizations can lower operational costs by reducing inefficiencies and waste, while also streamlining the use of materials and energy [30]. This often leads to innovation, increased productivity, and sustainable business growth.

Enhanced Organizational Reputation: Commitment to sustainable procurement can bolster an organization's image and credibility with key stakeholders—such as customers, investors, and employees [31]. Responsibility, environmental and social responsibility fosters trust, attracts ethically minded consumers, and enhances employee morale and retention.

Reduced Long-Term Risk and Costs: Taking a forward-looking approach to procurement enables organizations to mitigate risks linked to environmental degradation, climate change, and resource depletion [31]. This proactive stance helps prevent costly interruptions, enhances

resilience, and contributes to the long-term sustainability and competitiveness of the organization.

2.6.Critical Gaps in EPD Use for LCA Comparisons

Although Environmental Product Declarations (EPDs) are powerful tools for material comparison, especially under procurement programs like Buy Clean, their current structure and use, pose several challenges for accurately comparing reinforcement materials, particularly when comparing steel to FRPs (GFRP and CFRP).

Non-uniform Functional Units

A major limitation in using existing EPDs is the lack of a standardized functional unit across products. For example:

- Steel rebar EPDs typically use 1 metric ton (1,000 kg) as the functional unit.
- GFRP EPDs often use 1 linear meter, 1 kg, or even per bar.
- CFRP LCAs in literature use mass-based or project-specific prestress strand assumptions.

This lack of uniformity makes apples-to-apples comparisons difficult unless values are normalized to a common performance-based functional unit (e.g., 1 m^3 of reinforced concrete achieving a specific flexural strength).

System Boundary Inconsistencies

System boundary definitions (e.g., cradle-to-gate, cradle-to-site) vary significantly between EPDs:

- Some steel EPDs include only A1–A3.
- Others (e.g., Nucor) also report A4 transport and even partial C modules.
- GFRP and CFRP data frequently exclude A4–C4 altogether.

These boundary mismatches can exaggerate or hide impacts, particularly transportation emissions (A4), which disproportionately affect heavier materials like steel.

Resin System Variability in FRPs

Another challenge unique to FRPs is variation in resin systems:

- GFRP may use vinyl ester, polyester, or epoxy, each with different environmental profiles.
- CFRP typically uses epoxy or advanced thermoset systems, which differ in curing time, thermal energy, and chemical additives.

Most FRP EPDs report generic "polymer matrix" emissions, but detailed resin formulation is often undisclosed, creating uncertainty in life cycle datasets.

Manufacturing Location and Grid Factors

Electricity source (renewables vs fossil) dramatically affects GWP and ADPf:

- Steel produced in the EU or U.S. using EAF and renewable energy yields lower emissions.
- GFRP pultrusion in countries with coal-based electricity (e.g., India, China) has a higher GWP even if resin content is low.

Few EPDs clearly state grid mix, and even fewer report energy consumption per kg of product, complicating regional comparisons.

Lack of CFRP-Specific PCRs and EPDs

CFRP materials suffer from the absence of verified, public EPDs. Most data comes from peer-reviewed LCAs or private industry reports, for example [24], [32]. As a result, there is no harmonized method for cradle-to-gate reporting. Variability in carbon fiber sourcing (PAN-based vs pitch-based) introduces ±50% GWP swing. This creates a major transparency gap in CFRP lifecycle assessment and limits its inclusion in procurement frameworks.

Limitations in Impact Categories

Current PCRs and EPDs typically report: GWP, ADPf, AP and EP. However, categories like toxicity (human and eco), microplastic release, or fiber degradation are often excluded — yet may be more relevant for polymers than for metals. This distorts the sustainability profile of FRPs in cradle-to-grave analysis.

Summary and Implications for Research

This chapter has provided a detailed review of the environmental, structural, and lifecycle performance of steel, GFRP, and CFRP reinforcements in reinforced concrete structures. The review highlights the following key insights:

- Steel rebar remains dominant globally but is environmentally costly due to corrosion, weight, and energy-intensive production.
- GFRP is a proven, cost-effective alternative in decks and piles exposed to aggressive environments, offering lower lifecycle emissions and maintenance.
- CFRP is optimal for high-performance applications, such as prestressed bridge girders and marine piles, though currently hindered by cost and data transparency.

LCA tools and EPDs enable quantitative comparison but suffer from functional unit inconsistency, system boundary divergence, and limited FRP-specific PCR guidance.

Case studies affirm the practical viability of FRPs in large-scale bridge construction and provide empirical data supporting their expanded use.

These findings reinforce the need for a rigorous, harmonized LCA approach—using verified EPDs, normalized data, and performance-based functional units—to compare reinforcement alternatives fairly and support low-carbon infrastructure development.

3. METHODOLOGY

1.1. Research Approach

This study adopts an LCA-based comparative framework in accordance with ISO 14040/44 and EN 15804 standards. The overall methodological structure is illustrated in Figure 3.1, which outlines the two main stages of analysis, the data sources, and the integration of quantitative and qualitative approaches. The methodology is divided into two primary components: (1) a product-stage analysis (A1–A3), focusing on material-level comparisons between GFRP and steel rebars, and (2) a construction-stage and structural-level analysis (A4–A5) based on the real-world Harkers Island Bridge replacement project in the United States.

The comparative lifecycle assessment utilized secondary data, including Environmental Product Declarations (EPDs), design documents, and stakeholder interviews (notably with Balfour Beatty) to evaluate the environmental performance of steel- and FRP-reinforced concrete bridge components—specifically decks, piles, and girders. A mixed-method approach was utilized, combining quantitative LCA calculations with qualitative insights derived from expert interviews and case study analysis.

Contractor interviews were instrumental in understanding construction-phase logistics, including differences in handling, transportation, and installation efficiency between steel and GFRP reinforcement, particularly during stages A4–A5. The goal was to holistically compare the environmental impacts of reinforcement types—steel strands and rebars versus GFRP rebars and CFRP strands—across the A1 to A5 life cycle stages.

For the product-stage comparison, global EPDs were collected using varying declared units: per kilogram for GFRP and per metric ton for steel. These units were subsequently harmonized to enable a fair and direct comparison within the LCA framework. Additionally, to capture long-term environmental implications, the reference service life was assumed to be 50 years for steel-reinforced elements and 100 years for FRP-reinforced elements. Steel elements were assigned a 12% maintenance GWP increment based on literature-based assumptions [33], whereas FRP components were assumed to require no maintenance over their lifespan due to their corrosion resistance and durability.

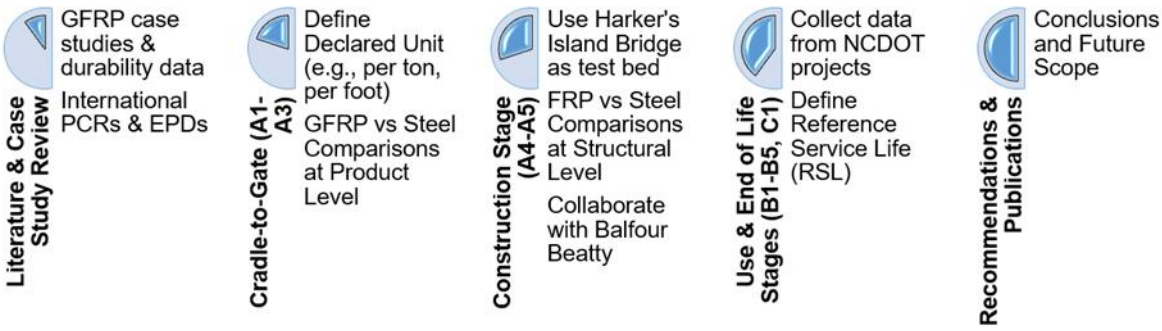


Figure 3.1:Methodology

3.1.Data Collection at the Material level (A1-A3)

Firstly, GWP data for steel and GFRP rebars was collected from EPDs from all over the world, in a holistic approach to have an understanding of how steel and GFRP rebars perform in GWP at the product stage(A1-A3). Steel EPDs had a declared unit per metric ton while GFRP EPDs had a declared unit per kg. Subsequently, after normalizing the GWP impacts to the same declared unit, GWP impacts comparisons(steel vs GFRP rebars) per metric ton was performed, irrespective of a specific diameter. Along with this, a GWP/m comparison - global warming potential of producing a 1m long, 10mm diameter rebar(steel vs GFRP) was done to figure out which of the two materials had a significant GWP during the production stage (raw material extraction,transport and manufacturing).

The typical LCA setup for the product stage (A1–A3) is illustrated in Figure 3.2, which is based on the ATP GFRP EPD. This schematic highlights the system boundaries considered in the analysis and ensures alignment with EN 15804 guidelines for cradle-to-gate modeling.

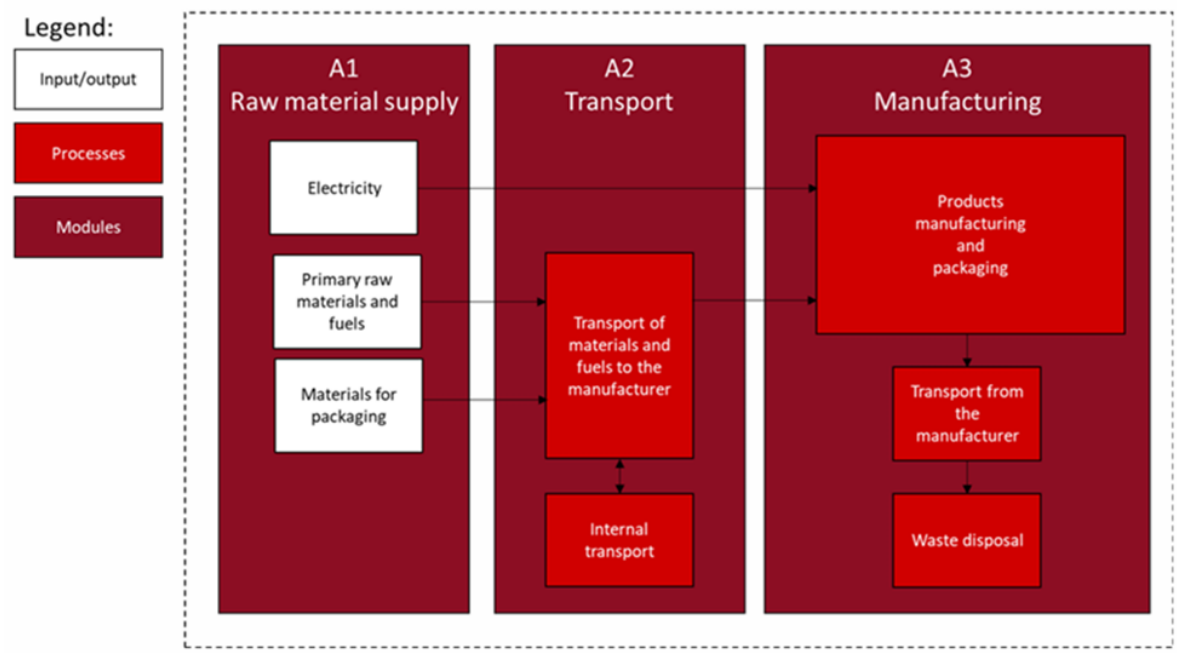


Figure 3.2:Typical Product Stage (A1-A3) module setup (ATP-GFRP-EPD)

Table 3.1 below shows EPDs under Consideration(Steel and GFRP) and their respective locations.

Table 3.1: EPDs under Consideration(Steel and GFRP) and their respective locations

STEEL EPDs	Location	GFRP EPDs	Location
DONGKUK	Korea	ATP	Italy
HYTEN	UK	SOLIDIAN	Croatia
CRSI (Industry Wide)	USA	MATEENBAR	Saudi Arabia
EXPRESS	UK	VROD	Canada
DEACERO	Latin,North America	DEXTRA	China
HERCULES	Sweden		
NATSTEEL	Singapore		
THAMES	UK		
CELSA	UK		
NUCOR	USA		

To enable product-stage comparisons, GWP values for steel reinforcement were compiled from published steel EPDs. These values are expressed per metric ton, consistent with the declared unit of most steel EPDs, and form the baseline for subsequent comparisons with GFRP reinforcement. Table 3.2 presents the GWP data for steel rebars on a per-metric-ton basis.

Table 3.2: GWP values for Steel EPDs used for comparisons per Metric Ton

STEEL EPDs	Global Warming Potential (kg CO_2 eq)
DONGKUK (Korea)	1340
EXPRESS (UK)	483
DEACERO (Americas)	406
HERCULES (Sweden)	478
CRSI (USA)	854
HYTEN (UK)	554

To complement the per-ton analysis, the functional unit was scaled to a 1-meter-long, 10 mm diameter steel rebar. This enables a practical comparison of carbon burdens associated with producing reinforcement at the element level rather than purely by mass.Table 3.3 summarizes the calculated GWP values per metre of steel rebar.

Table 3.3: GWP/ton values for Steel EPDs used for comparisons per Metre (10mm diameter)

STEEL EPDs	Global Warming Potential (kg CO_2 eq)
NATSTEEL (Singapore)	511
THAMES STEEL (UK)	549
CELSA STEEL (UK)	437
NUCOR STEEL (USA)	364

In parallel, GFRP rebar GWP values were compiled from international EPDs, which typically declare impacts per kilogram. These were normalized to a per-metric-ton basis to allow direct comparisons with steel.Table 3.4 provides the GWP data for GFRP rebars expressed per metric ton.Subscripts V and E represents vinylester and epoxy resin respectively.

Table 3.4: GWP values per metric ton for GFRP EPDs used for all comparisons vs Steel

GFRP EPDs	Global Warming Potential (kg CO_2 eq)
ATP_V (Italy)	3360
$SOLIDIAN_E$ (Croatia)	2710
$MATEENBAR_V$ (Saudi Arabia)	2340
$VROD_V$ (USA,Canada)	3090
$DEXTRA_V$ (China)	2630

Finally, to provide an application-oriented comparison, GWP values for producing a 1-meter-long, 10 mm diameter rebar were calculated for both steel and GFRP. This metric facilitates direct evaluation of material choice at the component level. Table 3.5 compares the per-meter GWP of steel and GFRP rebars at the product stage (A1–A3). All Rebars (Steel and GFRP) had the same constant volume and diameter of 7.85E-05 m^3 and 0.01m respectively.

Table 3.5: GWP/Metre Data of 1m long, 10mm diameter Rebar for Steel and GFRP

EPDs	**(S)NAT**	**(S)THA**	**(S)CEL**	**(S)NUC**	**(GF)ATP**	**(GF)MAT**	**(GF)SOL**	**(GF)DEX**
Mass (kg/m)	0.617	0.617	0.617	0.613	0.165	0.165	0.168	0.173
Density (kg/m^3)	7850	7850	7850	7800	2100	2100	2140	2200
GWP/kg	0.511	0.549	0.437	0.364	3.36	2.34	2.71	2.37
GWP/m	**0.315**	**0.338**	**0.269**	**0.223**	**0.554**	**0.386**	**0.455**	**0.410**

The environmental impact results for both steel and GFRP rebars were reported based on a declared unit (per metric ton), which does not account for differences in material performance or application-specific functionality.

To ensure a valid and meaningful comparison, environmental impacts were expressed relative to a functional unit that reflects equivalent service or structural contribution as shown in Table 3.6. A comparison of GWP/ unit strength(MPa)- the global warming potential per MPa of a 1m long, 10mm diameter rebar (Steel vs GFRP) was then executed (only EPDs specifying 10mm diameter were utilized for both steel and GFRP rebars) . All Rebars(Steel and GFRP) had the same constant volume and diameter of 7.85E-05 m^3 and 0.01m respectively.

Table 3.6: GWP/Unit Strength (MPa) Data of 1m long, 10mm diameter Rebar for Steel and GFRP

EPDs	(S)NAT	(S)THA	(S)CEL	(S)NUC	(GF)ATP	(GF)MAT	(GF)SOL	(GF)DEX
Mass(kg/m)	0.617	0.617	0.617	0.613	0.165	0.165	0.168	0.173
Density(kg/m^3)	7850	7850	7850	7800	2100	2100	2140	2200
GWP/kg	0.511	0.549	0.437	0.364	3.36	2.34	2.71	2.37
GWP/m	0.315	0.338	0.269	0.223	0.554	0.386	0.455	0.410
GWP/Unit Strength(1m)	**6.63E-04**	**6.67E-04**	**5.39E-04**	**5.57E-04**	**6.68E-04**	**4.06E-04**	**4.34E-4**	**4.18E-4**

One last analysis executed at the Material level, was the comparison of GWP/Ton(y-axis) vs Density/strength ratio (x-axis) of a 1m long, 10mm diameter rebar (Steel vs GFRP) as shown in Table 3.7. To have a composite view of both material efficiency and environmental intensity. The density/strength ratio serves as a proxy for material efficiency (lighter material for the same strength), where lower values indicated higher structural performance per unit mass, and was particularly relevant for comparative material assessment in structural design. All these analysis and comparisons were done and presented on the same graphs in excel (results analysis in chapter 4 of this thesis) so as to get an insight of how GFRP rebars perfoms in comparison to steel rebars from a functional perspective. These are the analysis executed at the product stage (A1-A3).

Table 3.7: GWP/Ton and Density/Strength Ratio values for Steel and GFRP

EPDs	GWP/Ton	Density/Strength Ratio
NAT (STEEL)	5.11E+02	1.65E+01
THAMES (STEEL)	5.49E+02	1.57E+01
CELSA (STEEL)	4.37E+02	1.57E+01
NUCOR (STEEL)	3.64E+02	1.95E+01
ATP (GFRP)	3.36E+03	2.53E+00
MATEENBAR(GFRP)	2.34E+03	2.21E+00
SOLIDIAN (GFRP)	2.71E+03	2.04E+00
DEXTRA (GFRP)	2.37E+03	2.24E+00

3.2.GWP Analysis at The Material Level(A1-A3)-GFRP vs STEEL Rebars

3.2.1. Global Warming Potential Comparisons per Metric Ton (A1-A3)

The A1–A3 stage comparison of GWP between GFRP and steel rebars shown in Figure 3.3, reveals a stark environmental contrast, with GFRP exhibiting significantly higher embodied carbon emissions across all assessed manufacturers.

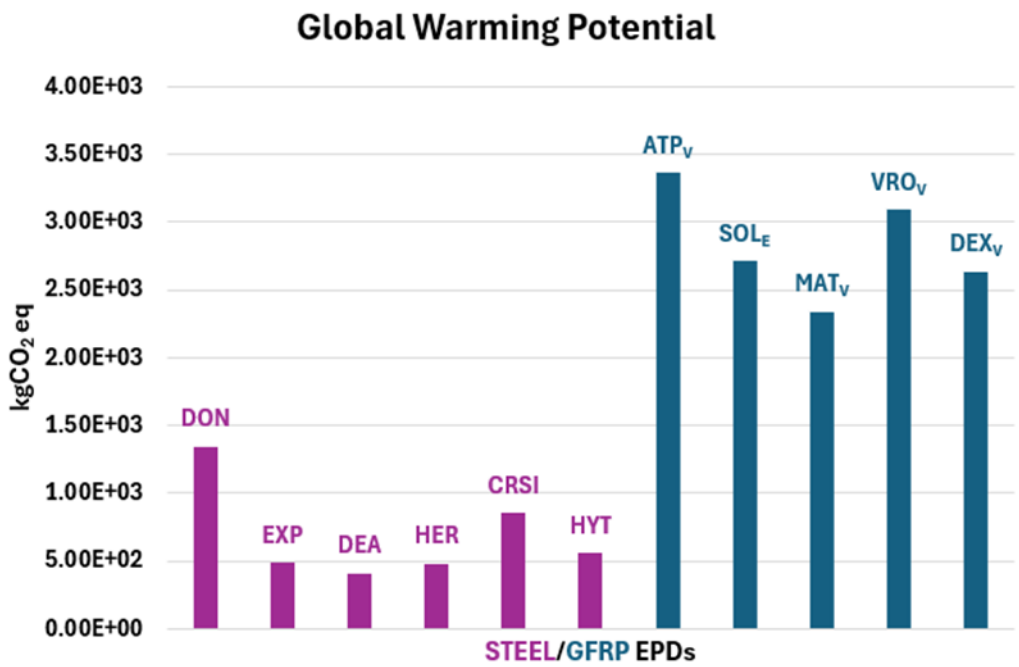


Figure 3.3:Global Warming Potential Comparisons per Metric Ton (A1-A3)

Steel rebars, particularly those produced in regions with cleaner electricity grids and electric arc furnace technology—such as EXP (UK), HER (Sweden), and DEA (Latin and North America)—show GWP values ranging from approximately 480 to 850 kg CO_2-eq per metric ton. In contrast, GFRP rebars, regardless of manufacturer, consistently exceed 2,300 kg CO_2-eq, with ATP_v (Italy) reaching a peak of ~3,360 kg CO_2-eq.

This disparity stems primarily from the resin and glass fiber components intrinsic to GFRP production. Resin synthesis—particularly vinyl ester—and glass fiber manufacturing are highly energy-intensive and rely heavily on fossil-based inputs [33]. Additionally, the regional electricity mix, and manufacturing efficiency contribute to variability among GFRP producers,

with MAT_v (Saudi Arabia) showing comparatively lower impacts likely due to newer production infrastructure and localized material sourcing.

Overall, while GFRP offers functional advantages such as corrosion resistance and potential service life extension, the A1–A3 results demonstrate a clear environmental disadvantage at the manufacturing stage compared to steel, emphasizing the importance of full life cycle assessment when evaluating FRP sustainability.

Limitations of this comparison:

- The environmental impact results for both steel and GFRP rebars are reported based on a declared unit (per metric ton), which does not account for differences in material performance or application-specific functionality. As such, these results should not be used for direct comparison without considering how the physical and mechanical properties of each material influence their functional performance in a given structural context. To ensure a valid and meaningful comparison, environmental impacts must be expressed relative to a functional unit that reflects equivalent service or structural contribution.
- Furthermore, variations in EPD programs and methodologies (as outlined in ISO 14025) may affect data consistency, and declarations from different sources may not be fully comparable. Accordingly, a subsequent comparative analysis based on a functional unit—specifically 1 meter of 10 mm diameter steel and GFRP rebar—is presented to enable a practical comparison of carbon burdens associated with producing reinforcement at the element level (GWP per metre) rather than purely by mass and also provide a more accurate assessment from a performance-based perspective (GWP per Unit Strength).

3.2.2. GWP/Metre and GWP/Unit Strength of Rebar Comparisons (A1 A3)

The use of yield strength for steel and tensile strength for GFRP in structural design arises from their fundamentally different mechanical behaviors. Steel is a ductile material, meaning it undergoes significant plastic deformation before failure. Its yield strength marks the onset of permanent deformation, making it a crucial design parameter; structures are typically designed to remain below this threshold to ensure serviceability and safety under load, without experiencing irreversible deformation.

Conversely, GFRP is inherently brittle and exhibits no plastic deformation prior to failure. It lacks a well-defined yield point and behaves elastically until it suddenly fractures. As such, its tensile strength—representing the ultimate stress the material can withstand before rupture—is the governing limit for design. Engineers must ensure that applied stresses remain well below this tensile strength to avoid abrupt and catastrophic failure. This distinction in design philosophy is widely recognized in composite design standards and literature, including ACI 440.1R-15 and other guidelines for non-metallic reinforcement systems.

a. GWP/Metre of 1m Rebar Comparisons (A1-A3)

The comparative analysis of GWP per metre for 10 mm diameter rebars as shown in Figure 3.4, reveals that, at the A1–A3 product stage, steel rebars generally exhibit lower cradle-to-gate emissions than their GFRP counterparts.

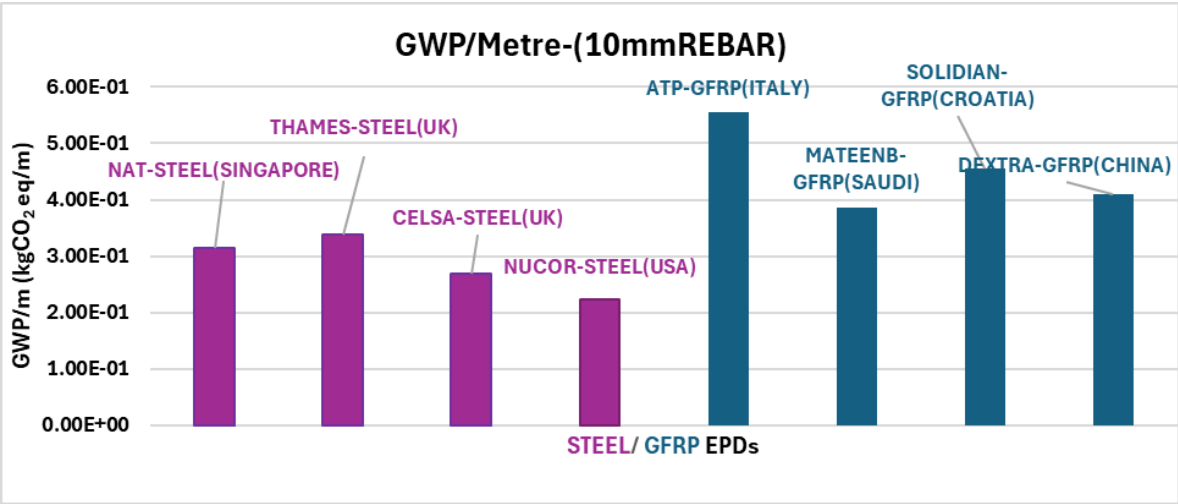


Figure 3.4:GWP/Metre of 1m of 10 mm diameter Rebar (A1-A3)

Steel rebars from producers such as Nucor (USA), CELSA (UK), and NatSteel (Singapore) demonstrate GWP values ranging from approximately 0.26 to 0.35 $kgCO_2eq/m$, with the lowest emission observed for Nucor, likely due to its use of electric arc furnace technology and high recycled steel content, both of which are well-documented to reduce embodied carbon significantly.

Conversely, GFRP rebars—particularly those from ATP (Italy), Solidian (Croatia), Dextra (China), and Mateenbar (Saudi Arabia)—present higher emissions per metre, ranging between 0.39 and 0.56 $kgCO_2eq/m$. This is largely attributable to the energy-intensive production of

synthetic resin matrices (epoxy or vinyl ester) and glass fiber reinforcements, which dominate the environmental footprint of GFRP products. Among the GFRP producers, ATP-GFRP displayed the highest per-metre GWP, which may reflect regional disparities in energy mix, manufacturing scale, or resin formulation [2]. While steel rebars show an environmental advantage at this stage of analysis, this per-metre comparison does not account for differences in strength-to-weight ratios, corrosion resistance, or expected service life. Therefore, for a more comprehensive sustainability evaluation, GWP must also be normalized by mechanical performance or functional unit metrics.

b. GWP/Unit Strength of 10mm Rebar(A1-A3).

The cradle-to-gate (A1–A3) GWP normalized per unit tensile strength (actual rupture strength), ($kgCO_2eq/MPa$) of 1m long, 10 mm diameter rebars as shown in Figure 3.5, reveals that GFRP rebars generally offer superior environmental efficiency compared to their steel counterparts when assessed on a performance basis [13], [24].

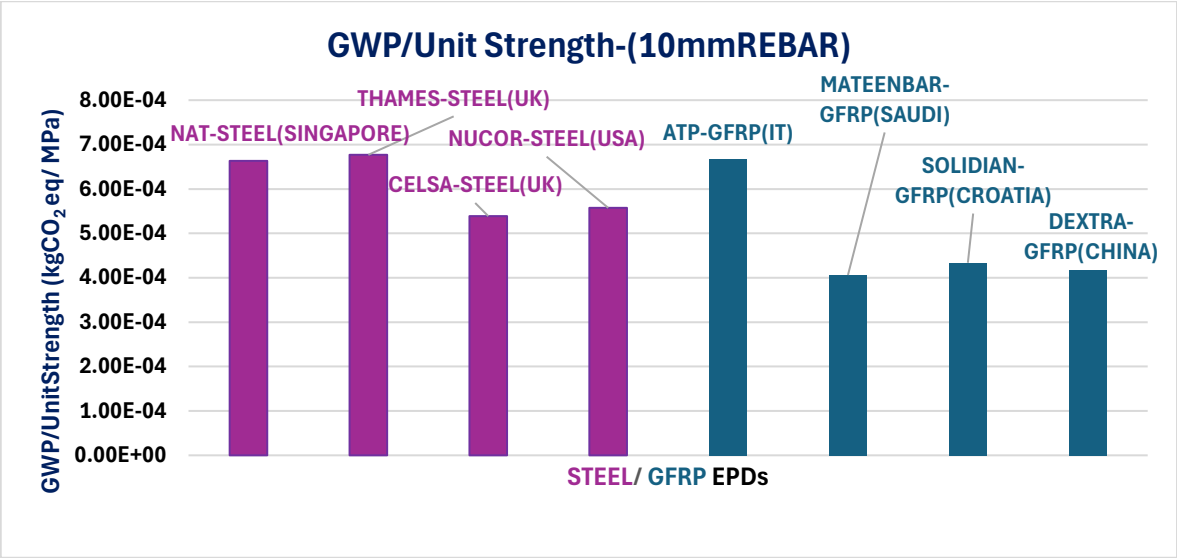


Figure 3.5:GWP of 10mm diameter Rebar per Unit Strength

Steel rebars across various producers—including NAT Steel (Singapore), Thames Steel (UK), CELSA (UK), and Nucor (USA)—exhibited GWP/unit strength values ranging between approximately 5.3×10^{-4} to 6.7×10^{-4} $kgCO_2eq/MPa$, reflecting the embodied emissions per unit of load-bearing capacity. In contrast, most GFRP rebar producers—such as Mateenbar (Saudi Arabia), Solidian (Croatia), and Dextra (China)—demonstrated significantly lower GWP/unit strength values, clustering between 3.9×10^{-4} and 4.3×10^{-4} $kgCO_2eq/MPa$, indicating more

environmentally efficient tensile performance. Notably, ATP-GFRP (Italy) presented a comparatively higher GWP/unit strength, suggesting that variations in resin type (e.g., vinyl ester vs epoxy), production energy sources, and manufacturing efficiency can significantly influence GFRP's embodied emissions [33]. These results reinforce the importance of performance-based normalization in LCA of reinforcement materials, as mass-based comparisons can obscure the environmental benefits of materials like GFRP, which combine high tensile strength with low density and corrosion resistance. Consequently, from a structural efficiency and emissions intensity perspective, GFRP rebars provide a lower GWP per unit of mechanical utility, supporting their application in sustainable infrastructure, particularly in aggressive environments where durability is paramount [13].

3.2.3. GWP/Ton--Density/Strength Ratio Comparisons (A1-A3)

When normalized against the density-to-strength ratio, a critical metric for evaluating structural material efficiency, GFRP rebars demonstrate distinct advantages over traditional steel reinforcement despite exhibiting higher mass-based Global Warming Potential as shown in Figure 3.6.

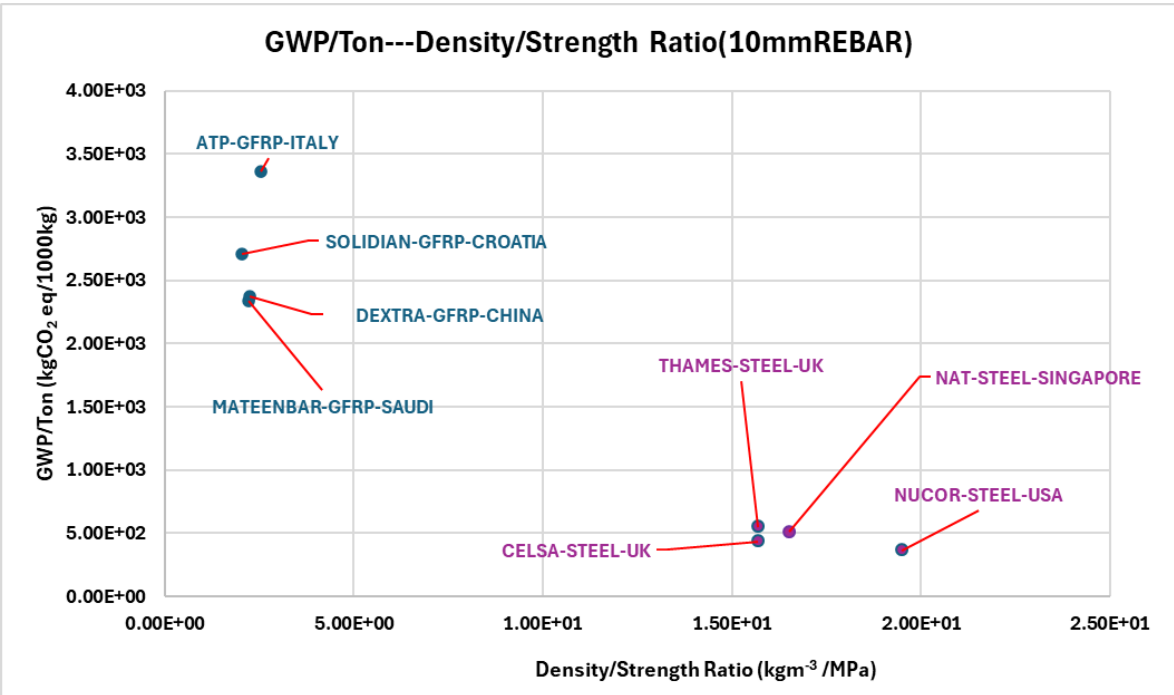


Figure 3.6:GWP/Ton-Density/Strength Ratio Comparisons (A1-A3

As shown in the comparative plot, steel rebars—owing to their high density (~7850 kg/m³) and moderate yield strengths (~500 MPa)—exhibit significantly higher density-to-strength ratios, ranging from approximately 15.7 to 19.5 kg/m³·MPa. Correspondingly, their GWP per ton lies between 360–590 $kgCO_2eq$/ton, reflecting efficiencies in steelmaking processes such as electric arc furnace recycling in regions like the UK and USA. In contrast, GFRP rebars exhibit much lower density-to-strength ratios (~3.5–5 kg/m³·MPa) due to their low density (~2100 kg/m³) and high tensile strengths (up to 1000 MPa), but incur substantially higher GWPs per ton, ranging from ~2270 to over 3360 $kgCO_2eq$/ton. This apparent carbon penalty is primarily attributed to the energy-intensive production of glass fibers and polymeric resins (epoxy or vinyl ester) [32].

However, when structural performance is considered—particularly in applications requiring high specific strength or corrosion resistance, the carbon efficiency of GFRP rebars improves significantly. For example, producers such as Mateenbar (Saudi Arabia) and Dextra (China) demonstrate lower GWP-to-structural-efficiency ratios, indicating that GFRP can outperform steel on a per-strength-delivered basis in specific applications, especially in aggressive environments where corrosion resistance and reduced mass offer long-term sustainability advantages. These findings align with broader LCA literature that emphasizes the importance of moving beyond mass-based comparisons toward functionally normalized assessments for accurate environmental benchmarking [25].

3.3. Data Collection and GWP Analysis at Construction Stage (A4-A5)- Balfour Beatty

This section provides a detailed comparative discussion of the environmental and practical implications of using steel versus GFRP rebars during the A4 (transportation) and A5 (construction/installation) stages of bridge construction. The comparison integrates findings from two primary sources: firsthand insights from Balfour Beatty, the contractor involved in the Harkers Island Bridge replacement project, and the documented Hall River Bridge project case study analyzed by [15]. Since the contractor had experience working with both steel and GFRP Rebars in the construction of steel and GFRP reinforced bridges, they provided insights and comparative data on the advantages and disadvantages of working with both steel and GFRP at the A4-A5 stage.

Transportation Impacts and Logistics

Transportation of materials plays a crucial role in the embodied carbon of the A4 stage. GFRP's lower density (approx. 2,100 kg/m³) compared to carbon steel (approx. 7,850 kg/m³) enables a greater quantity of reinforcement to be transported per truckload, significantly reducing the number of required trips. Balfour Beatty noted that although more GFRP pieces might be needed for equivalent volume coverage due to different mechanical properties, the lighter weight substantially reduces fuel use and transport-related emissions.
However, the contractor also notes that unloading GFRP requires more caution, typically involving cranes and specialized equipment to prevent surface fiber damage. This increases time and energy use during offloading, slightly mitigating the transportation GWP savings. In contrast, steel's robustness enables more rapid unloading with forklifts and minimal concern for damage, though this would not be the case for epoxy coated rebar that also needs to be treated more carefully on the construction site to avoid damaging the coating for corrosion purposes.Regardless of steel type used, a higher GWP footprint is expected due to its weight and associated emissions during trucking.

Storage and Site Logistics

Material vulnerability during storage further differentiates the two reinforcements. While uncoated carbon steel can be stored without protection in temperate climates, epoxy-coated steel—common in marine or coastal environments, as was the case in the Harkers Bridge construction, —requires protection from UV radiation to prevent degradation of the coating. Epoxy coatings, while offering corrosion resistance, contribute additional embodied carbon to steel's lifecycle.

GFRP, on the other hand, while non-corrosive, is inherently UV-sensitive due to the polymer resin matrix. Both Balfour Beatty and [15] stress the need to store GFRP under opaque, UV-resistant covers if exposed outdoors, especially beyond four months [34]. Moreover, GFRP should be kept on clean, level, and non-staining surfaces, requiring greater logistical care as per ACI 440.1R-15 requirement.

Handling, Flexibility, and Onsite Workability

The contrast in handling characteristics is one of the most significant between GFRP and steel. Due to GFRP's lower stiffness and higher brittleness, special care is required during handling and lifting. [15] used steel spreader beams to prevent GFRP cage deformation, emphasizing the need for specific tools to maintain structural integrity during placement. Installation of GFRP presented both advantages and challenges. As noted by Balfour Beatty, GFRP was easier to cut, leading to more flexibility during modifications. Its non-corrosive nature meant no additional patching was required (in case there was need to repair cracks which usually form after casting), which streamlined certain remedial actions.

However, bending of GFRP bars was not possible on-site, unlike steel, necessitating pre-bent bars from manufacturers. This constraint introduces lead-time risk, as any design changes mid-construction may trigger delays, this requirement emphasized the importance of early planning [15].The use of traditional steel ties is discouraged for GFRP to avoid surface abrasion; plastic-coated ties or zip ties are standard practice. Furthermore, safety considerations were observed: while steel cutting involves spark generation—posing fire hazards—GFRP cutting was spark-free, albeit generating fiberglass dust, necessitating the use of protective clothing and respiratory masks.

Installation Efficiency and Safety

GFRP's lightweight enabled faster material handling and cage placement. [15] reported an approximate 20% improvement in installation productivity (measured in ft/h/laborer) compared to steel. Additionally, Balfour Beatty noted GFRP was easier and safer to cut using handheld tools, eliminating the sparks generated by steel cutting, which are a fire hazard.

However, safety risks with GFRP were also documented. Workers required PPE such as long sleeves and masks due to airborne fiberglass particles during cutting. Furthermore, installation stability posed issues—GFRP's lower density increased buoyancy during concrete vibration, risking displacement. [15] mitigated this with additional plastic chairs and rubber-tipped vibrators to prevent surface damage to the bars. These issues contrast with steel cages, which typically remain stable due to their higher density and stiffness.

Procurement Complexity and Schedule Risk

Procurement lead time is a critical consideration in construction planning. FDOT specifications for GFRP require vendor preapproval and batch testing upon delivery, which were cited as contributors to schedule elongation [15]. Balfour Beatty echoed this challenge, noting the inability to make last-minute geometric adjustments due to the inflexibility in rebar bending. GFRP's ease of cutting and preassembly allowed faster setup, especially in deck and bent cap cages. However, optimal outcomes rely on preplanning and skilled labor.

Poor equipment deployment or inexperienced handling can negate GFRP's productivity advantages. Steel, by contrast, is more readily available and adaptable on-site, streamlining procurement, reducing risk and fewer regulatory delays. Additionally, steel's ability to be spliced and welded onsite provides structural flexibility, while GFRP is limited to overlapping splices and adhesives.

Lifecycle Durability and Maintenance Considerations

A compelling argument in favor of GFRP reinforcement is its resistance to corrosion. Balfour Beatty emphasizes that the all-FRP Harkers Island Bridge was designed for a 100-year lifespan with zero anticipated corrosion-related maintenance. This contrasts with the previously replaced steel-reinforced bridges (Nos. 96 and 73), which suffered significant degradation due to chloride-induced corrosion over 50 years. Balfour Beatty reported that while GFRP bridges like the Harkers Island Bridge are designed for 100 years without maintenance, traditional steel-reinforced structures such as the replaced Bridges No. 96 and 73 exhibited significant degradation after 50 years due to corrosion. A study by Benzecry [36], also supports GFRP durability in bridge decks, where bridges in service for at least 15-20 years, showed a reduction in strength of only 2.17%.

GFRP structures eliminate the need for corrosion-related repairs and associated lifecycle emissions. The contractor also identified a maintenance limitation: locating GFRP using Ground Penetrating Radar is difficult due to its non-metallic composition [35]. This poses challenges for future overlays or deck modifications. Steel's ferromagnetic nature, while making it easier to detect, also contributes to higher lifecycle costs and environmental burdens.

3.4. Data Collection at the Structural level -Case Study (Harkers Island Bridge)

As part of the structural level analysis (Steel vs FRP reinforcement) of this study, environmental material data (A1-A3) was projected to a real case study (Harkers Island Bridge-USA) by considering specific structural elements (deck, piles, girders). Bridge design documents were provided by project principal investigator (PI); which included the reinforcement details, element dimensions, and span lengths for both the replaced steel-reinforced bridges (Bridge No. 96 and Bridge No. 73) and the new all-FRP reinforced Harkers Island Bridge. The steel-reinforced bridges shown in Figure 3.7, which had 13.72m long spans and were decommissioned after 50 years of service due to corrosion-related structural deficiency, consisted only of a cored slab deck and piles (four per bent, each 14.63m long).

Bridge No. 96

- Built 1970
- Superstructure Replacement 2013
- Functionally Obsolete

Bridge No. 73

- Built 1969
- Posted SV 24, TTST 37
- Structurally Deficient

Figure 3.7: Replaced Steel-Reinforced Bridges(BridgeNo-96,73)

In contrast, the Harkers Island Bridge (FRP-reinforced) shown in Figure 3.8, designed with 30.48m long spans and a projected 100-year service life without maintenance, comprises a deck, five piles each-30.48m long, and four girders per span.

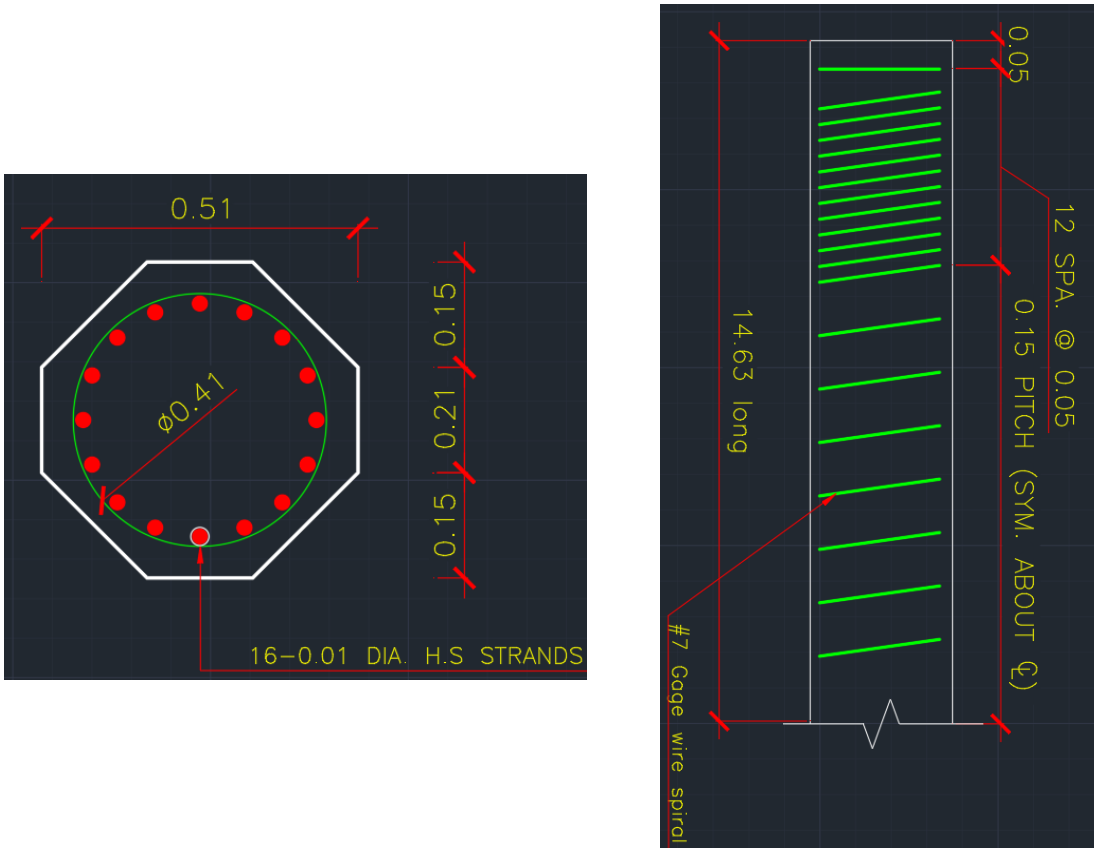
Figure 3.8: New-All FRP Reinforced Harkers Island Bridge

For the sake of uniformity and to ensure direct comparisons, note that the dimensions of all the structures considered below are in **metres**.

3.4.1. Structural Element Designs:

a) Existing /Replaced Bridge (Steel Reinforced)

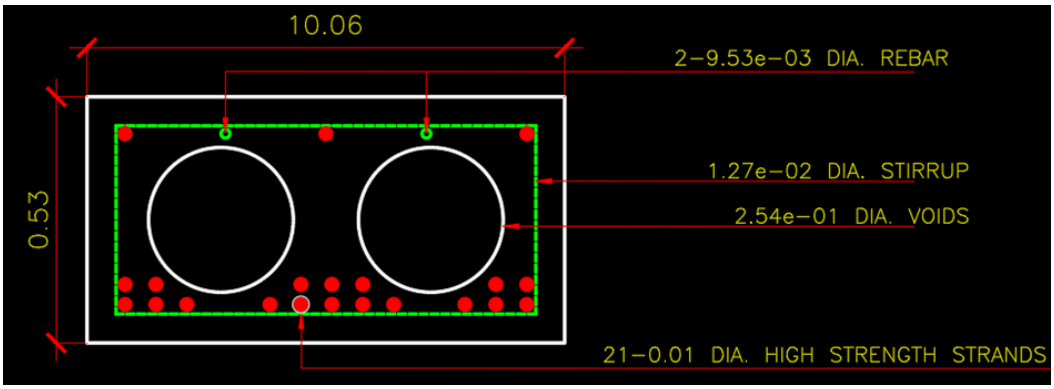
Figure 3.9 Shows the cross section and elevation dimensions (in metres) along with the reinforcement distribution of the Steel Reinforced Pile.



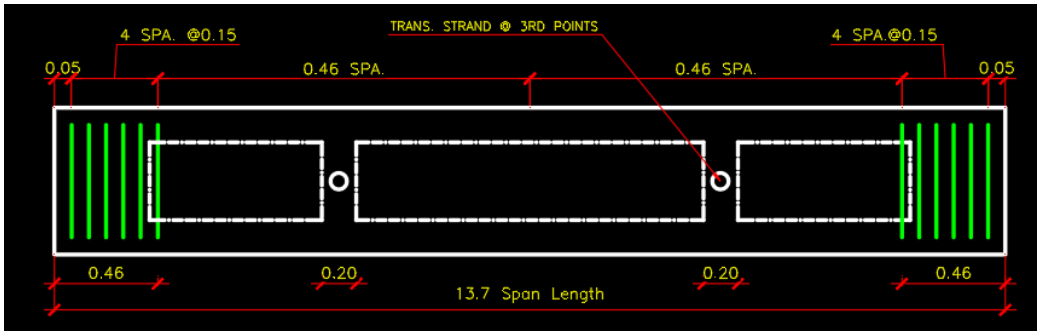
(a) Pile Section View (b) Pile Elevation

Figure 3.9:Steel Reinforced Pile (**m**)

Figure 3.10 Shows the cross section and elevation dimensions (in metres) along with the reinforcement distribution of the Steel Reinforced Cored Deck.



(a) Cored Slab Section View

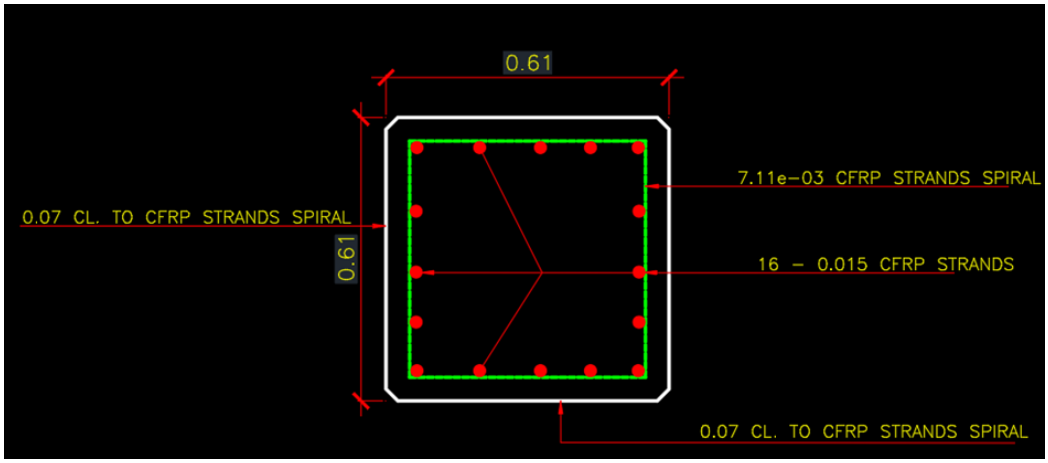


(b) Deck Elevation

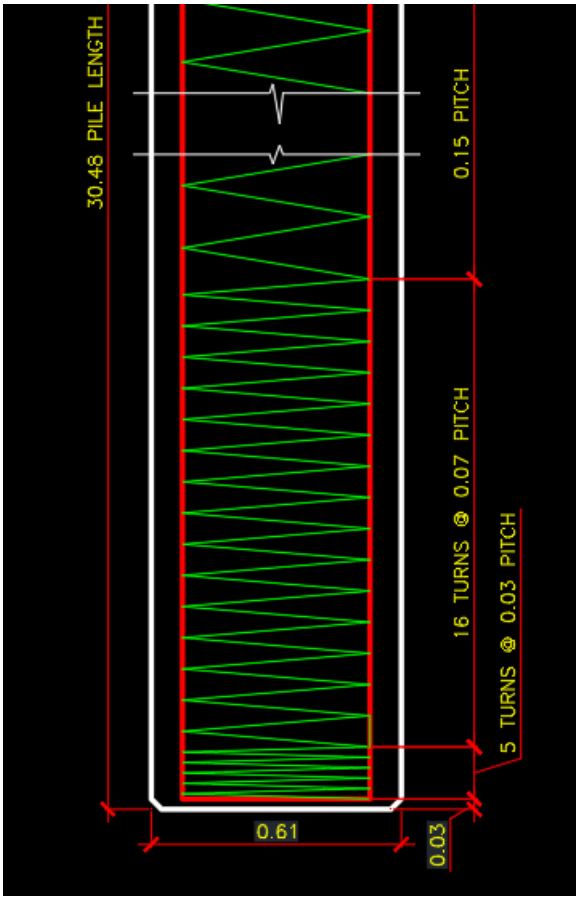
Figure 3.10:Steel Reinforced Deck (**m**)

b) New Bridge (All- FRP Reinforced)

Figure 3.11 Shows the cross section and elevation dimensions (in metres) along with the reinforcement distribution of the CFRP Reinforced Pile.



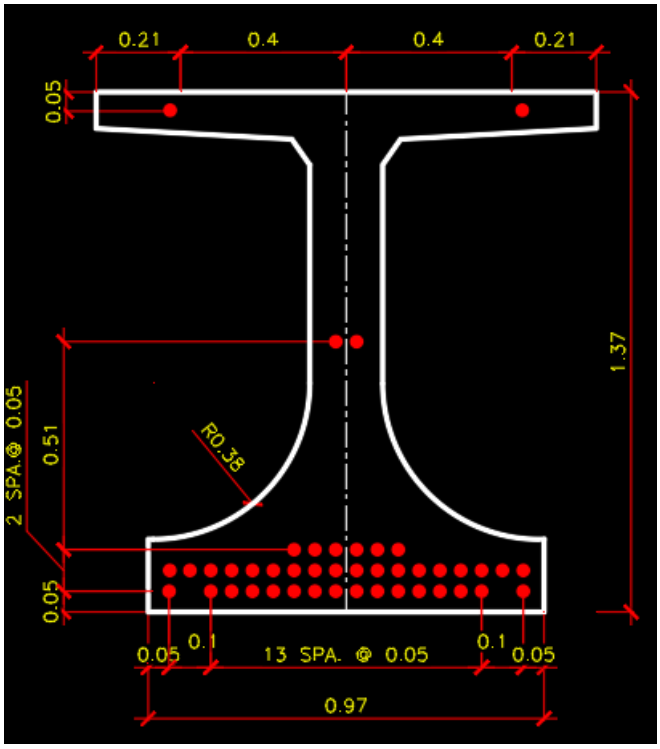
(a) Pile Section View

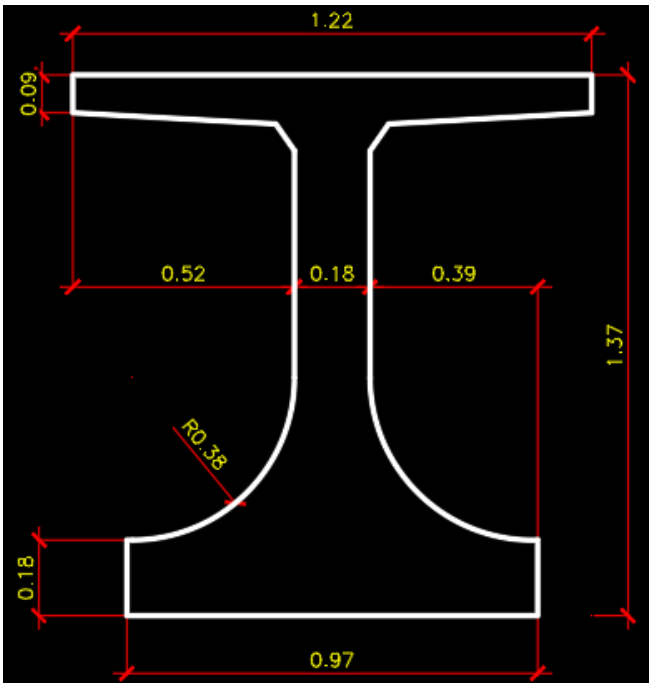


(b) Pile Elevation

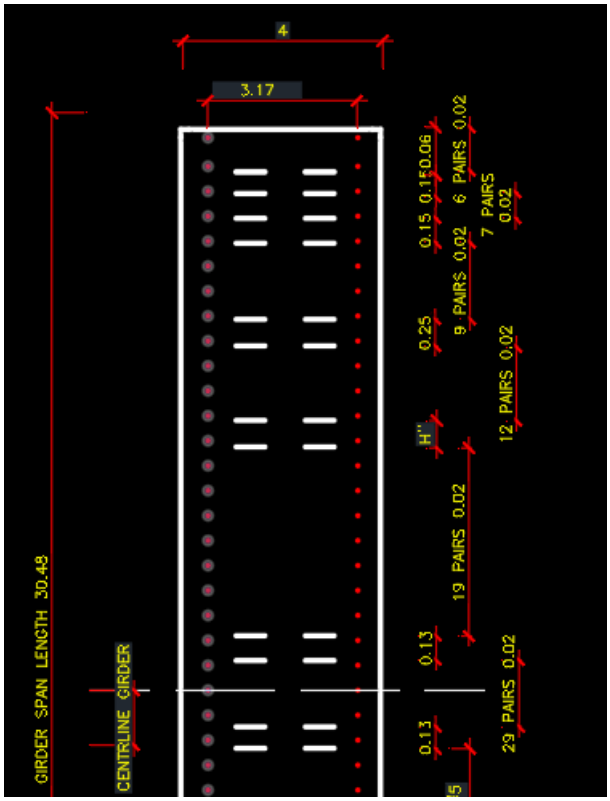
Figure 3.11:CFRP Reinforced Pile (**m**)

Figure 3.12 Shows the cross section and elevation dimensions (in metres) along with the reinforcement distribution of the CFRP (longitudinal strands) and GFRP Rebar Reinforced Girder.





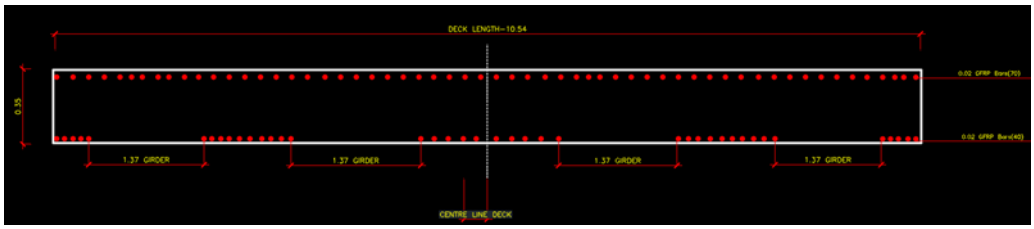
(a) Girder Section View



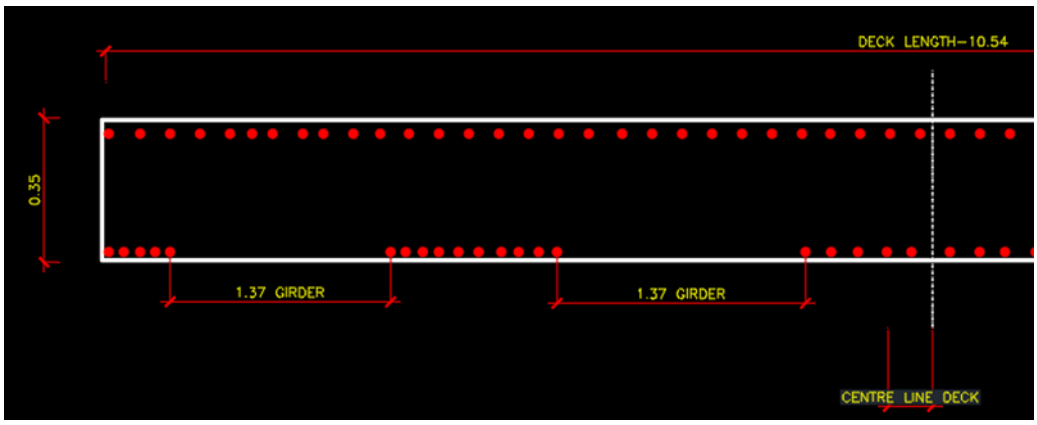
(b) Girder Elevation

Figure 3.12:CFRP and GFRP Reinforced Girder (**m**)

Figure 3.13 Shows the cross-section dimensions (in metres) along with the reinforcement distribution of the GFRP Rebar Reinforced Deck.



(a) Deck Section View



(b) Deck Section View at Centre line

Figure 3.13:GFRP Reinforced Deck (**m**)

To ensure a meaningful and functionally comparable assessment, it was agreed with the project Principal Investigator and the FRP++ Supervision team, to conduct a comparative life cycle analysis at the structural element level, focusing on the deck, piles, and girders. The PI provided moment capacity values for each of these structural elements in both the steel-reinforced and FRP-reinforced bridges shown in Table 3-8 and 3-9. The nominal moment capacity (often denoted as Mn) is the theoretical maximum bending moment that a structural member (e.g., pile, slab, girder) can resist before reaching its ultimate limit state, assuming ideal material behavior and section properties.These moment capacities were computed using the Response-2000 software, enabling performance-based normalization of the Global Warming Potential (GWP) data.

Table 3.8: Bridge no 73 and 96 Bridge (Steel RC)- Structural Element Capacities

No	Element	Geometry	Cross Section Dimensions (m)	# Strands	Estimated Nominal Moment Capacity (kNm)
1	Pile	Octagonal	0.5	16	337
2	Deck	Hollow core	10 x 0.5	231	1023

Table 3.9: New FRP RC Bridge - Structural Element Capacities

No.	Element	Geometry	Cross Section Dimensions (m)	# Strands	Estimated Moment (kNm)	Nominal Capacity
3	Pile	Rectangular	0.6	16	791	
4	Girder	FIB	1.3	44	10033	
8	Deck	Flat slab	10.5 x 0.3		1084	

With regards to the dimensions of the girder, its section height of 1.37m was mentioned in Table 3.9. Subsequently, the volumes of each structural element (deck, piles, girders) were calculated using Microsoft Excel. This entailed extracting precise measurements and reinforcement specifications directly from the structural design drawings provided for each bridge. From these volumes, the volume of reinforcement materials (e.g., steel rebars, GFRP rebars, steel strands, CFCC cables, #7 gage wire) as well as the volume of concrete per element were determined.

3.4.2. Structural Elements Component Volumes (Reinforcement and Concrete):

a) EXISTING BRIDGE (STEEL RC):

Table 3.10 shows the mechanical properties of steel strands, rebars, concrete that make up the Steel Reinforced Pile and Deck of the Replaced Bridge.

Table 3.10:Steel RC Bridge Components (steel strands, rebars, concrete) **Properties**:

	Tensile Strength (MPa)	Tensile Modulus (GPa)	Compressive Strength (MPa)	Concrete Strength At stress transfer (MPa)
HighStrength Steel Strands	1861	200		
Concrete			34	13
Steel Rebars	413			

STRUCTURAL ELEMENT # 1: PILE (Steel Reinforced)

Respectively Table 3.11 and Table 3.12 show the longitudinal and transverse reinforcement volumes included in the Steel Reinforced Pile of the Replaced Bridge.

Table 3.11: Steel RC Pile **Longitudinal** Reinforcement **Volumes**

Steel Strands	Amount	Dia(mm)	Area(m^2)	Length of pile(m)	Volume(m^3)
Longitudinal Reinforcement	16	11.18	9.81E-05	14.63	**2.30E-02**

Table 3.12: Steel RC Pile **Transverse** Reinforcement **Volumes**

Transverse Reinforcement (#7 Gage wire)	Pitch	Dia(mm)	Pile Dia(m)	No of turns	Total length(m)	Area(m^2)	TotalVolumeof reinforcement(m^3)
Top	5.08E-02	3.67	0.41	12	15.32	1.06E-05	1.62E-04
Middle	1.52E-01	3.67	0.41	88	112.35	1.06E-05	1.19E-03
Bottom	5.08E-02	3.67	0.41	12	15.32	1.06E-05	1.62E-04
					143.00	**3.17E-05**	**1.51E-03**

Total Volume of Reinforcement in a Pile = 2.45E-02 (m^3).

STRUCTURAL ELEMENT #2: DECK

Table 3.13 show the longitudinal and transverse reinforcement volumes included in the Steel Reinforced Deck of the Replaced Bridge.

Table 3.13: Steel RC Bridge Deck Reinforcement Volumes

Steel Reinforcement	Amount	Dia(mm)	Area(m^2)	Length(m)	Total Volume of Reinforcement (m^3)
Rebars	2	9.53	7.13E-05	13.72	**2.15E-02**
Strands	21	11.1	9.70E-05	13.72	**3.07E-01**
Stirrups	40	12.7	1.27E-04	2.13	**1.19E-01**

Total Volume Of Reinforcement In Cored Slab Deck = 4.48E-01 (m^3).

VOLUME OF CONCRETE IN STEEL RC BRIDGE ELEMENTS (PILE, DECK):

Table 3.14 show the Concrete volumes included in the Steel Reinforced Pile and Deck of the Replaced Bridge respectively.

Table 3.14: Steel RC Bridge **Volume of Concrete** (Pile, Deck)

	Length(m)	Depth(m)	Span length(m)	Area(m^2)	VolumeofStructure (m^3)	VolumeofConcrete (m^3)
Pile	0.51	0.51	14.63	2.58E-01	3.79	**3.77**
CoreSlab	10.06	0.53	13.72	5.26	72.20	**71.75**

The deck area - area of voids in the deck = 5.37 – 1.01E-01= **5.26 (m^3).**

The volume of concrete in the cored slab deck/span = **71.75 (m^3).**

NEW BRIDGE(FRP -RC):

Table 3.15 shows the mechanical properties of CFRP strands, GFRP rebars, and Concrete that make up the FRP Reinforced Pile,Girder and Deck of the New all FRP-RC Bridge.

Table 3.15:FRP RC **Component** (CFRP strands, GFRP rebars, Concrete) **Properties:**

	Tensile Strength (MPa)	Tensile Modulus (GPa)	Compressive Strength (MPa)	Concrete Strength at stress transfer (MPa)
CFRP Strands (Longitudinal)	2000	150		
CFRP Strands (Spiral)	2000	160		
GFRP Rebars	935	60		
Concrete			34	13

STRUCTURAL ELEMENT # 1: PILE (CFRP-Reinforced)

Respectively Table 3.16 and Table 3.17 show the longitudinal and transverse reinforcement volumes included in the CFRP Reinforced Pile of the New all FRP- Reinforced Bridge.

Table 3.16: FRP RC Pile **Longitudinal** Reinforcement **Volumes**

CFRP Strands	Amount	Diameter(mm)	Area(m^2)	Length of pile(m)	Volume(m^3)
Longitudinal	16	15.24	1.82E-04	30.48	**8.90E-02**

Table 3.17:FRP RC Pile **Transverse** Reinforcement **Volumes**

CFRP Stirrups	Pitch(m)	Dia(mm)	No of turns	Total length(m)	Area(m^2)	Total Volume of reinforcement(m^3)
1st Section	2.54E-02	7.11	5	2.32E-01	3.97E-05	9.23E-06
2nd Section	7.62E-02	7.11	16	7.46E-01	3.97E-05	2.96E-05
Middle	1.52E-01	7.11	182	8.57E+00	3.97E-05	3.40E-04
3rd Section	7.62E-02	7.11	16	7.46E-01	3.97E-05	2.96E-05
4th Section	2.54E-02	7.11	5	2.32E-01	3.97E-05	9.23E-06
				1.05E+01		**4.18E-04**

Total Pile Volume of Reinforcement = 8.94E-02 (m^3).

STRUCTURAL ELEMENT # 2: GIRDER(CFRP and GFRP Reinforced)

Table 3.18 show the longitudinal and transverse reinforcement volumes included in the CFRP and GFRP Reinforced Girder of the New all FRP- Reinforced Bridge.

Table 3.18:FRP RC **Girder** Reinforcement **Volumes**

Component	Amount	Dia(mm)	Area(m^2)	Length(m)	Total Volume of Reinforcement (m^3)
CFRP Strands	44	15.24	1.82E-04	30.48	2.45E-01
GFRP Rebars	135	16.00	2.01E-04	4.27	1.16E-01
					3.60E-01

The Total Volume Of Reinforcement In Girder = 3.60E-01 (m^3).

STRUCTURAL ELEMENT # 3: DECK (GFRP Reinforced)

Table 3.19 shows the longitudinal and transverse reinforcement volumes included in the GFRP Reinforced Deck of the New all FRP Reinforced Bridge.

Table 3.19:FRP RC **Deck** Reinforcement **Volumes**

GFRP Rebars	Top	Bottom	Diameter (mm)	Area (m^2)	Span length (m)	Volume (m^3)	Total volume of reinforcement (m^3)
Longitudinal reinforcement	70	40	19.05	2.85E-04	30.48	8.69E-03	9.56E-01
Transverse reinforcement	100	100	19.05	2.85E-04	10.54	3.00E-03	6.01E-01
						Deck Reinforcement Total Volume(m^3)	**1.56**

VOLUME OF CONCRETE-NEW BRIDGE FRP-RC (PILE, GIRDER, DECK):

Table 3.20 show the Concrete volumes included in the FRP Reinforced Pile,Girder and Deck of the New all FRP-Reinforced Bridge respectively.

Table 3.20:FRP RC Bridge **Volume of Concrete** (Pile, Girder, Deck)

	Length(m)	Depth(m)	Span(m)	Area(m^2)	VolumeofStructure Element(m^3)	Volume of concrete (m^3)
Pile	0.61	0.61	30.48	3.72E-01	11.33	**11.24**
Girder		4.5	30.48	6.01E-01	18.32	**17.96**
Deck	10.54	0.35	30.48	3.69	112.61	**111.05**

Volume of structure element – volume of reinforcement = volume of concrete **(m^3)**

3.4.3. Material-specific GWP data Collection

Given that the study is contextualized within North America and considering the region-specific nature of Life Cycle Assessment (LCA) data, the GWP values used for material components were sourced primarily from North American EPDs. For ready-mixed concrete and steel rebars, regional average values were retrieved from the EC3 tool hosted by Building Transparency [39]. The GWP of high-strength steel strands was derived by averaging values from three North American EPDs: Insteel, Sumiden, and Suncoast.

The GWP for GFRP rebars was collected from the Environmental Product Declaration published by VROD, a leading North American GFRP manufacturer. For #7 gage wire, values were sourced from the Celsa Circular Steel EPD, selected based on proximity to literature values and regional relevance. In the case of Carbon Fibre Composite Cable (CFCC), a range of GWP values was adopted in a scenario-based comparisons, from the 2022 fib article [23].

EXISTING BRIDGE (STEEL-RC) Components (Concrete, Steel rebars, Strands, Wire) GWP:

Table 3.21 shows the Global Warming Potential Coefficients of the Components making up the Replaced Steel Reinforced Bridge.

Table 3.21: Steel Reinforced Bridge Component GWP Coefficients

Component	Global Warming Potential Coefficient	Global Warming Potential ($kgCO_2eq/m^3$)
Concrete	316 $kgCO_2eq/yd^3$	413.18
Steel Rebars	903.89kg CO_2-eq/ton	7093.40
High Strength Steel Strands	1490 kg CO_2-eq/ton	11693.50
#7 Gage wire	564 kg CO_2-eq/ton	4451.65

NEW BRIDGE (FRP-RC) Components (Concrete, GFRP rebars, CFRP strands) GWP:

Table 3.22 shows the Global Warming Potential Coefficients of the Components making up the New all- FRP Reinforced Bridge.

Table 3.22: FRP- Reinforced Bridge Components GWP Coefficients

Component	Global Warming Potential Coefficient	Global Warming Potential ($kgCO_2eq/m^3$)
Concrete	316 $kgCO_2eq/yd^3$	413.18
GFRP Rebars	1490 kgCO2eq/ton	6482.26
CFRPStrands (Scenario1)	19.25 ton CO_2/ton	28888.80
CFRPStrands (Scenario2)	9.85 ton CO_2/ton	14771.3

3.4.4. Global Warming Potential per Structural Element

With all material-specific GWPs compiled, the next step was to calculate the total GWP per structural element (pile, girder, deck). This was achieved by multiplying the volume of each component (e.g., concrete, steel, GFRP) by its corresponding GWP coefficient ($kgCO_2eq/m^3$) [Material volumes × GWP coefficients = Total GWP per element] and summing the values to yield the total cradle-to-gate GWP for each element—pile, deck, and girder—for both bridge types.

EXISTING BRIDGE (STEEL-RC) Global Warming Potential Per Structure:

Table 3.23 shows the Global Warming Potential per single Pile of the Replaced Steel-RC Bridge.

Table 3.23:GWP per **Steel Reinforced Pile**

PILE Component	**Volume(m^3)**	**Global Warming Potential ($kgCO_2eq/m^3$)**	**G W P-Impact per Pile ($kgCO_2eq$)**
Concrete	3.77	413.18	1556.13
#7 Gage wire	1.51E-03	4451.65	1.90E-01
High Strength Steel Strands	2.30E-02	11693.50	268.52
		Total G W P-Impact per Pile ($kgCO_2eq$)	**1824.84**

Table 3.24 shows the Global Warming Potential of the Deck per span, of the Replaced Steel-RC Bridge.

Table 3.24:GWP Per **Steel Reinforced Deck**

DECK Component	**Volume(m^3)**	**Global Warming Potential ($kgCO_2eq/m^3$)**	**G W P-Impact per Slab ($kgCO_2eq$)**
Concrete	71.75	413.18	29645.95
Steel Stirrups	1.19E-01	7093.40	843.56
High Strength Steel Strands	3.07E-01	11693.50	3593.33
Steel Rebars	2.15E-02	7093.40	152.52
		Total G W P-Impact per Slab ($kgCO_2eq$)	**34235.36**

The Global Warming Potential Of The Cored Slab Deck/Span = 34235.36 $kgCO_2eq$.

NEW BRIDGE(FRP-RC) Global Warming Potential Per Structure:

Table 3.25 shows the Global Warming Potential per single Pile of the New all FRP-RC Bridge.

Table 3.25:GWP per **CFRP Reinforced Pile**

PILE Component	**Volume(m^3)**	**GlobalWarming Potential($kgCO_2eq/m^3$)**	**G W P-Impact per Pile ($kgCO_2eq$)**
Concrete	11.24	413.18	4643.05
CFRP Strands	8.94E-02	28888.80	2582.03
		Total G W P-Impact per Pile ($kgCO_2eq$)	**7225.08**

Table 3.26 shows the Global Warming Potential of a single Girder of the New all FRP-RC Bridge under 2 different scenarios.

Table 3.26:GWP/Girder under scenario 1 and 2

	GWP/Girder ($kgCO_2$ eq)
Scenario 1: CFRP At 28 888.80 $kgCO_2$ eq/m^3	15239.28
Scenario 2: CFRP At 14771.3 $kgCO_2$ eq/m^3	11785.58

Table 3.27 shows the Global Warming Potential per single Girder of the New all FRP-RC Bridge.

Table 3.27:GWP per **FRP (CFRP and GFRP) -Reinforced Girder**

GIRDER Component	**Volume(m^3)**	**Global Warming Potential ($kgCO_2eq/m^3$)**	**G W P-Impact per Girder ($kgCO_2eq$)**
Concrete	17.96	413.18	7420.92
CFRP Strands	2.45E-01	28888.80	7067.36
GFRP Rebars	1.16E-01	6482.26	751.00
		Total G W P-Impact per Girder($kgCO_2eq$)	**15239.28**

Under scenario 2, the total GWP of each girder would be = 11 785.58 $kgCO_2eq$.

Table 3.28 shows the Global Warming Potential of the Deck per span of the New all FRP-RC Bridge.

Table 3.28:GWP per **GFRP Reinforced Deck**

DECK Component	**Volume(m^3)**	**Global Warming Potential ($kgCO_2eq/m^3$)**	**G W P-Impact per Deck ($kgCO_2eq$)**
Concrete	111.05	413.18	45884.09
GFRP Rebars	1.56	6482.26	10089.70
		TotalGWP-Impact per Deck($kgCO_2eq$)	**55973.79**

Considering that the Superstructure of the New FRP-RC Bridge consists of both a deck and girders, the total GWP of the Deck: 55973.79 + 15239.28 x 4 girders = **116 930.91 $kgCO_2eq$** Under scenario 2, the total GWP of the deck would be **= 55 973.79 + 11 785.58 x 4 girders = 103 116.11$kgCO_2eq$.**

3.5.GWP Analysis at Structural Level: Harkers Island Bridge Case Study

3.5.1. Global Warming Potential Normalization per Structural Element

To facilitate functional comparisons, these raw GWP values were normalized in two key ways. Firstly, the GWP per structural element were divided by the respective structural element length, yielding GWP per metre for piles and GWP per span length for the deck. Secondly, GWP was divided by the moment capacity of piles, resulting in a GWP per unit of structural performance. These normalized values allowed for a more insightful comparison between the steel and FRP systems from both material efficiency and engineering perspectives.

3.5.2. Structural Element # 1: Deck (Steel-RC vs GFRP-RC)

a) SCENARIO 1 COMPARATIVE METRICS: DECK (STEEL-RC vs GFRP-RC)

The Table 3.28 presents data of GWP per bridge deck, at the A1–A3 stage (product stage), for two functionally equivalent concrete bridge decks located in the same coastal region of North Carolina under scenario 1. Owing to the range of the GWP of Carbon fibre composite cable from literature [23], 2 scenarios were utilized in this analysis, since CFRP was included in the girders which make up the superstructure of the new all-FRP reinforced bridge deck. Scenario 1: with CFRP, GWP considered as 19.25 tonCO_2/ton which translates to a GWP coefficient of 28 888.80kgCO_2eq/m^3 and scenario 2 (best case scenario): considering the GWP of CFRP as 9.85 tonCO_2/ton which translates to a GWP coefficient of 14771.3 kgCO_2eq/m^3.

Table 3.28:GWP of each Deck (Steel-RC vs GFRP-RC)

	GWP/Deck (kgCO_2eq)	**GWP/Span length**
Existing Bridge (Steel-RC)	**34235.36**	2496
New Bridge (GFRP-RC)	**116 930.91**	3836

GWP/DECK AT INITIAL CONSTRUCTION:

The attached Figure 3.14 presents a comparative analysis of GWP of each bridge deck (steel-RC vs GFRP-RC), at initial construction [Material volumes × GWP coefficients = Total GWP per Deck] and summing the values to yield the total cradle-to-gate GWP for each deck, for both bridge types.

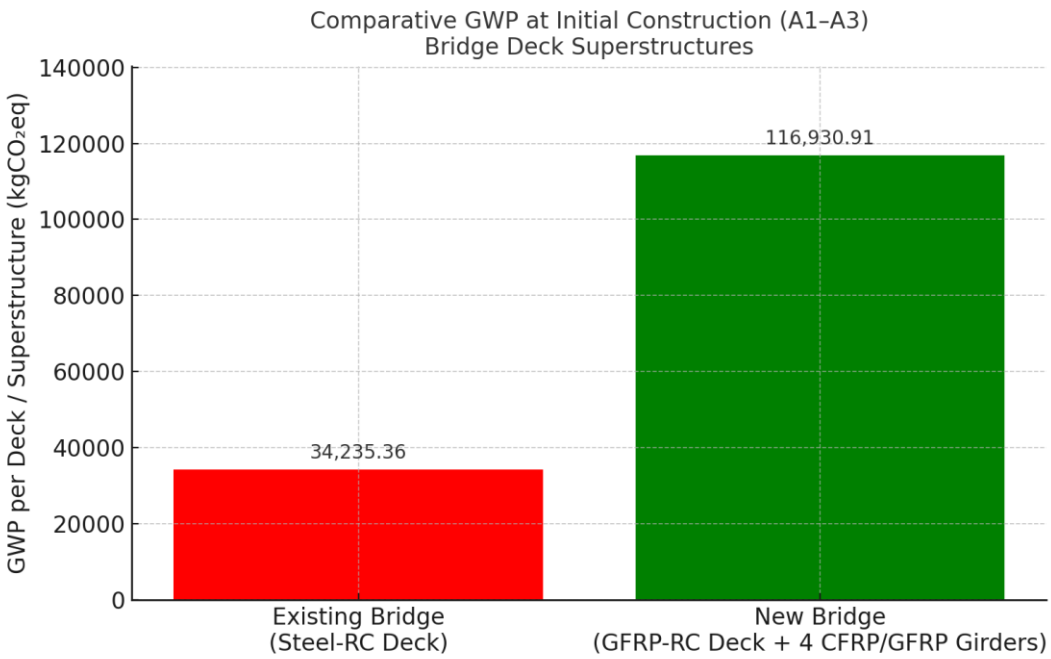


Figure 3.14:GWP (Steel- RC vs GFRP-RC Deck) at initial construction

The comparison of initial construction impacts reveals that the GFRP-RC bridge superstructure, which includes both the deck and four CFRP/GFRP-reinforced girders, exhibits a substantially higher cradle-to-gate GWP (116,930.91 $kgCO_2$-eq) compared to the steel-RC bridge deck (34,235.36 $kgCO_2$-eq). This difference, a factor of over three, is primarily driven by the inclusion of girders in the deck system and the inherently high embodied carbon of CFRP strands due to energy-intensive fibre production processes. While the steel-RC option shows a considerably lower GWP at the product stage, the FRP alternative demonstrates how the incorporation of multiple FRP-reinforced structural elements amplifies the environmental burden during initial construction, underlining the significance of reinforcement type and structural composition in shaping early-stage carbon footprints.

At the element level, the plot is a sum of unlike scopes (deck vs deck+girders), so it is not a like-for-like material substitution. At the bridge-system level, the new GFRP/CFRP superstructure enabled longer spans in the case study (30.48 m vs 13.72 m previously). Longer spans can cut pier/pile counts and reduce substructure quantities per route-kilometre. Those avoided substructure materials and future maintenance can partially (or wholly) offset the higher superstructure A1–A3—but only when the functional unit is the whole crossing (e.g., “per km of bridge with target design life”), not “per deck per span”.

GWP/SPAN LENGTH: STEEL-RC vs GFRP -RC DECK

The figure 3.15 compares the GWP per unit span length (kg CO_2eq/m) respectively, for two concrete bridge decks: the existing steel-reinforced bridge with a 13.72 m span and the new GFRP-reinforced bridge with a 30.48 m span.

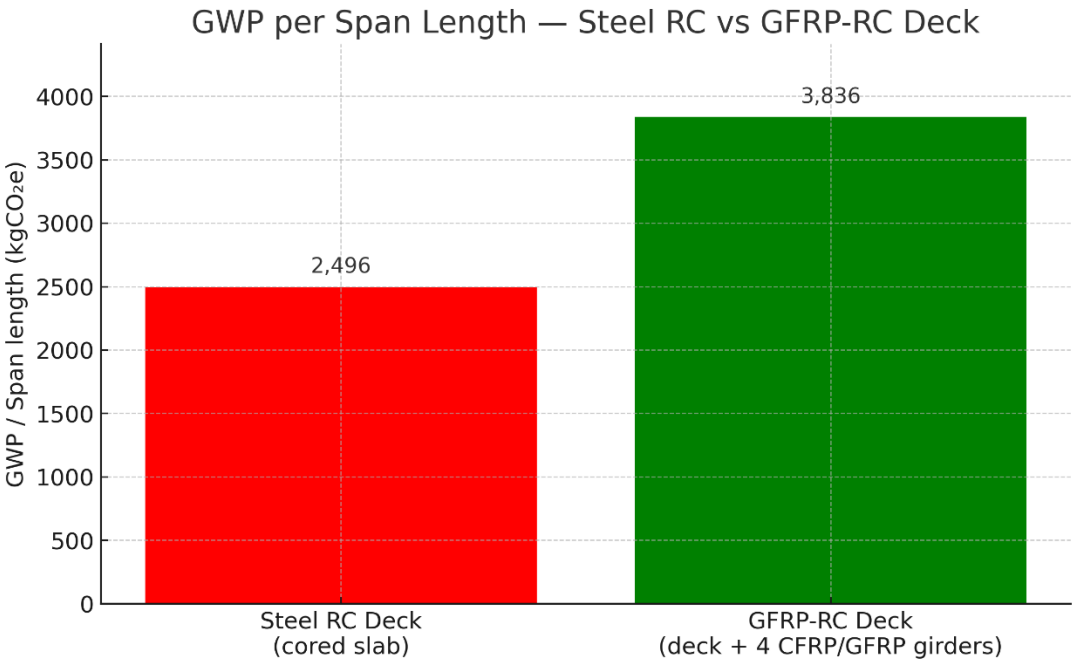


Figure 3.15:GWP (Steel- RC vs GFRP-RC Deck) per Span Length

On a per-span-length basis, the GFRP-RC alternative (deck + four girders reinforced with CFRP strands longitudinally and GFRP rebars transversely) exhibits a higher cradle-to-gate GWP than the existing steel-RC alternative (steel-strand prestressed cored slab deck alone):

- Steel-RC deck: 2,496 kgCO_2eq per span length
- GFRP-RC deck + girders: 3,836 kgCO_2eq per span length

This is an absolute difference of +1,340 kgCO_2eq per span length, i.e., the GFRP-RC superstructure is ~53.7% higher than the steel-RC option on this metric.

The higher GWP per span length observed for the GFRP-RC deck (3,836 vs 2,496 kgCO_2eq/m for steel-RC) is primarily a result of its fundamentally different design requirements: it spans more than twice the length (30.48 m vs 13.72 m), is designed for a higher load class, and therefore adopts a deck-plus-girder system with CFRP strands and GFRP rebars, whereas the steel alternative is a short-span cored slab deck. These factors inherently increase material mass

and product-stage emissions per metre, but do not reflect inefficiency. Thus, the per-metre metric is misleading for cross-system comparison, and a functionally equivalent basis (capacity or demand-normalized) would show clear efficiency gains for FRP. Moreover, the non-corrosive nature of FRP reinforcement implies substantially reduced maintenance over a 100-year life, likely strengthening its advantage once whole-life emissions are considered.

GWP/MOMENT CAPACITY: STEEL-RC vs FRP -RC DECK

Table 3.29 shows the GWP/Moment Capacity comparative data for the two Decks(Steel-RC vs FRP-RC).

Table 3.29: GWP/Deck and GWP/Moment Capacity Data(Steel-RC vs FRP-RC) Deck

	GWP/Deck ($kgCO_2eq$)	**Moment Capacity(kNm)**	**GWP/Moment Capacity**
Existing Bridge (Steel-RC)	**34235.36**	1023	33.5
New Bridge (FRP-RC)	**116 930.91**	18 439.1	6.3

As shown in the Figure 3.15, the steel-RC cored slab deck registers 33.5 $kgCO_2eq/kNm$, while the FRP-RC superstructure (4 CFRP/GFRP girders + deck) shows 6.3 $kgCO_2eq/kNm$.

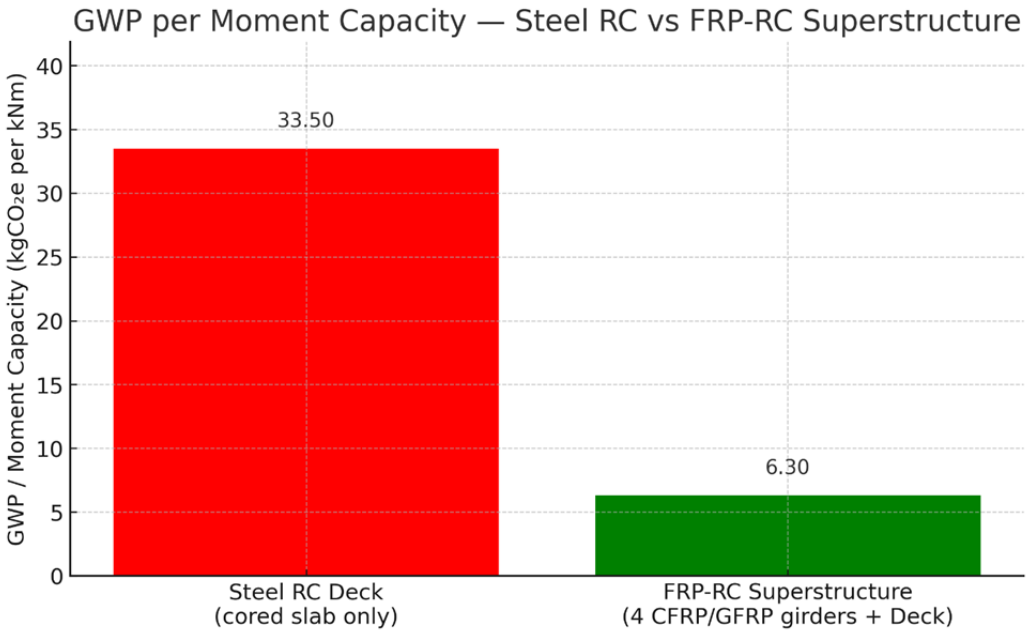


Figure 3.16: GWP/Moment Capacity(Steel-RC vs FRP-RC) Deck

This shows that the FRP system is about 5.3× more carbon-efficient per unit flexural capacity at the product stage (A1–A3).

Interpreted on this performance-normalized basis, the FRP design delivers substantially more flexural capacity per unit of embodied carbon at initial construction (A1–A3). This indicates superior carbon efficiency of the FRP superstructure for delivering structural utility, particularly relevant for longer spans or higher demand design requirements.

3.5.3. GWP/100 Years Per Deck: Steel-RC vs GFRP -RC

Lastly, a 100-year reference service life scenario was considered by combining the initial cradle-to-gate (A1–A3) GWP with estimated maintenance-related contributions as shown in Table 3.29.

Table 3.29 :GWP/100 RSL (Steel-RC vs GFRP-RC)

	GWP/Deck (kgCO_2 eq)	**At 100 years RSL**	**(+)12%**	**GWP/100 years**
Existing Bridge (Steel-RC)	34235.36	(**x2**)68470.73	+4108.24	**72578.97**
New Bridge (GFRP-RC)	116 930.91	0	0	**116 930.91**

The Figure 3.16 compares the GWP over a 100-year service life for the bridge decks of the existing steel-reinforced concrete (Steel-RC) bridge and the new GFRP-reinforced concrete (GFRP-RC) bridge, incorporating both initial A1–A3 emissions and estimated maintenance/overlay impacts.

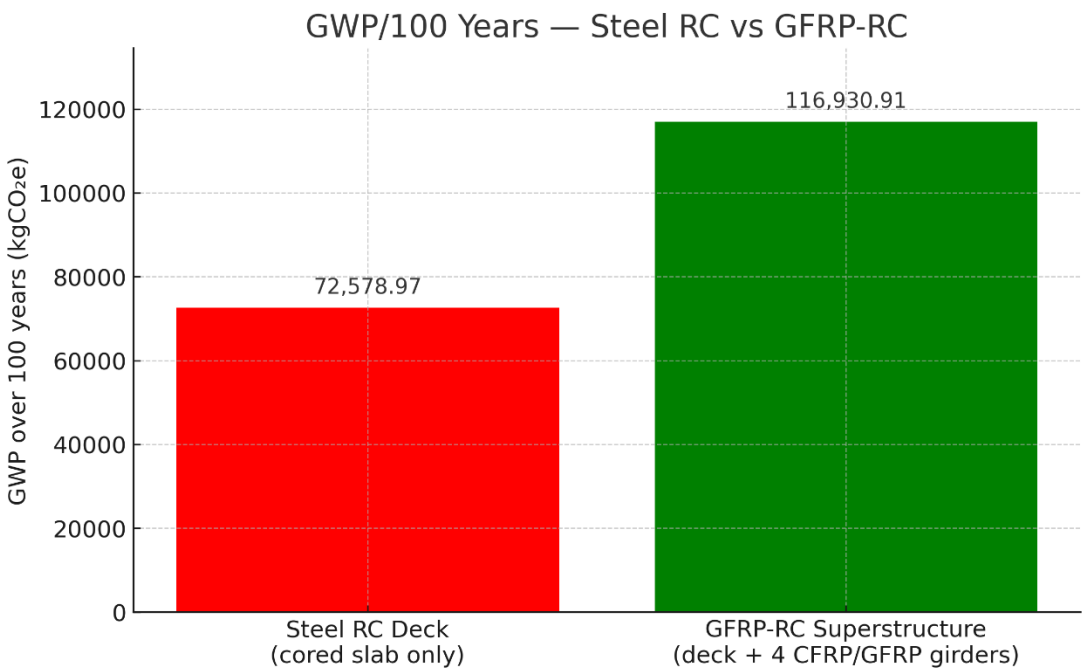


Figure 3.17:GWP/100 Years (Steel-RC vs GFRP-RC Deck)

The GWP over a 100-year service life for the steel-RC deck (cored slab only) is 72,578.97 $kgCO_2eq$, computed as 2× its A1–A3 embodied carbon (34,235.36) to reflect replacement at 100 years (68,470.73) + 12% of A1–A3 for maintenance (4,108.24). The FRP-intensive superstructure (GFRP-reinforced deck plus four girders reinforced with CFRP strands longitudinally and GFRP rebars transversely) is 116,930.91 $kgCO_2eq$, with 0% maintenance assumed over the reference life; thus GWP_{100} =A1–A3.

On this whole-life, deck-level basis the FRP alternative shows a higher total GWP (≈+61%) because its system boundary includes additional primary members (girders) and CFRP content with higher cradle-to-gate intensities, whereas the steel case represents only a short-span cored-slab deck. Consequently, GWP/100 mixes different structural systems and spans/loads and is not a functionally equivalent comparison; it informs absolute carbon outlay for the actual options as designed, rather than material efficiency. When normalized to structural function (e.g., $kgCO_2eq/kNm$), the same dataset will render the FRP system to be more carbon-efficient at A1–A3 due to its much higher delivered moment capacity, and durability advantages imply minimal maintenance—benefits that are not captured when totals are compared across non-like systems. The key implication is that procurement decisions should pair such whole-life totals with performance-normalized metrics (and explicitly stated system boundaries) to avoid

misattributing carbon differences that stem from span, load class, and memberization rather than intrinsic material inefficiency

Steel-RC Deck (per 100 years):

Initial GWP (A1–A3): 68,470.73 $kgCO_2eq$

(12%) Maintenance GWP: 4,108.24 $kgCO_2eq$

Total GWP over 100 years:

$$GWP\ Steel = 68{,}470.73 + 4{,}108.24 = 72{,}578.97\ kgCO_2eq \tag{1.1}$$

GFRP-RC Deck (per 100 years):

One-time total GWP (A1–A3): 55,973.79 $kgCO_2eq$

Maintenance GWP: Assumed negligible

$$GWP\ GFRP = 116\ 930.91\ kgCO_2eq \tag{1.2}$$

Break-Even Point Calculation:

Assuming linear accumulation of GWP for the steel-RC deck and comparing it against the fixed GFRP GWP:

Annual GWP rate for Steel-RC:

$$\frac{72{,}578.97}{100} = 725.79\ kgCO_2eq/year \tag{1.3}$$

Set equal to GFRP's total:

$$725.79x = 116\ 930.91 \tag{1.4}$$

$$x = \frac{116\ 930.91}{725.79} \cong 161\ years \tag{1.5}$$

Utilizing (33% of A1-A3) maintenance GWP of Steel-RC Deck over a 100-service life suggested by [40], the break-even point occurs at ≅ 146 years.

GWP/100 YEAR/SPAN LENGTH: STEEL-RC vs GFRP -RC DECK

Table 3.29 shows GWP/100 Year/Span Length: Steel-RC vs GFRP -RC Deck values after normalizing the GWP/100 year impact per each deck's span length i.e [GWP/100/13.72m] for the Steel-RC bridge deck.

Table 3.30:GWP/100 Year/Span Length: Steel-RC vs GFRP -RC Deck

	GWP/100 years	GWP/100years/Span Length
Existing Bridge (Steel-RC)	**72578.97**	**5290**
New Bridge (GFRP-RC)	**116 930.91**	**3836**

Normalizing 100-year GWP by span length yields 5,290 $kgCO_2eq/m$ for the steel-RC cored slab and 3,836 $kgCO_2eq/m$ for the FRP-intensive superstructure (deck + four CFRP/GFRP girders) as shown in Figure 3.17.

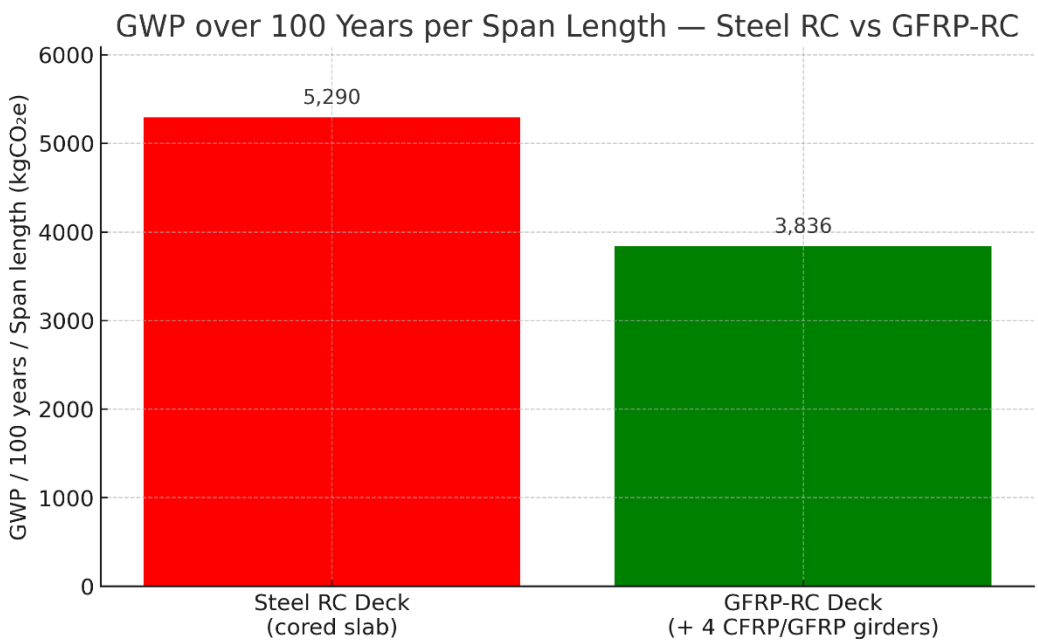


Figure 3.18:GWP/100 year/Span Length(Steel-RC vs GFRP-RC Deck)

Despite the FRP system's higher total GWP over 100 years, the length-normalized figure is ≈27.5% lower than steel, because this metric simultaneously accounts for (i) FRP's longer span (fewer spans per route) and (ii) the steel deck's maintenance/replacement burden embedded in

the 100-year total. Consequently, GWP/100 years per span length is a relevant measure for network-level planning: it expresses the embodied carbon required to deliver one metre of bridge over a century, revealing that the FRP alternative provides lower life-cycle carbon intensity per metre of bridge delivered.

b) SCENARIO 2 COMPARATIVE METRICS: DECK (STEEL-RC vs GFRP-RC)

The Table 3.30 presents data of GWP per bridge deck, at the A1–A3 stage (Steel-RC vs GFRP-RC) under scenario 2.

Table 3.31:GWP of each Deck (Steel-RC vs GFRP-RC)

	GWP/Deck (kgCO_2eq)	**GWP/Span length**
Existing Bridge (Steel-RC)	34235.36	2496
New Bridge (GFRP-RC)	103 116.11	3383

GWP/DECK AT INITIAL CONSTRUCTION:

Figure 3.18 shows Scenario 2, with the CFRP GWP coefficient reduced to 14,771.3 (from 28,888.8), the GFRP-RC superstructure (deck + four CFRP/GFRP girders) shows GWP/Deck = 103,116.11 kgCO_2eq, while the steel-RC cored slab deck remains at 34,235.36 kgCO_2eq.

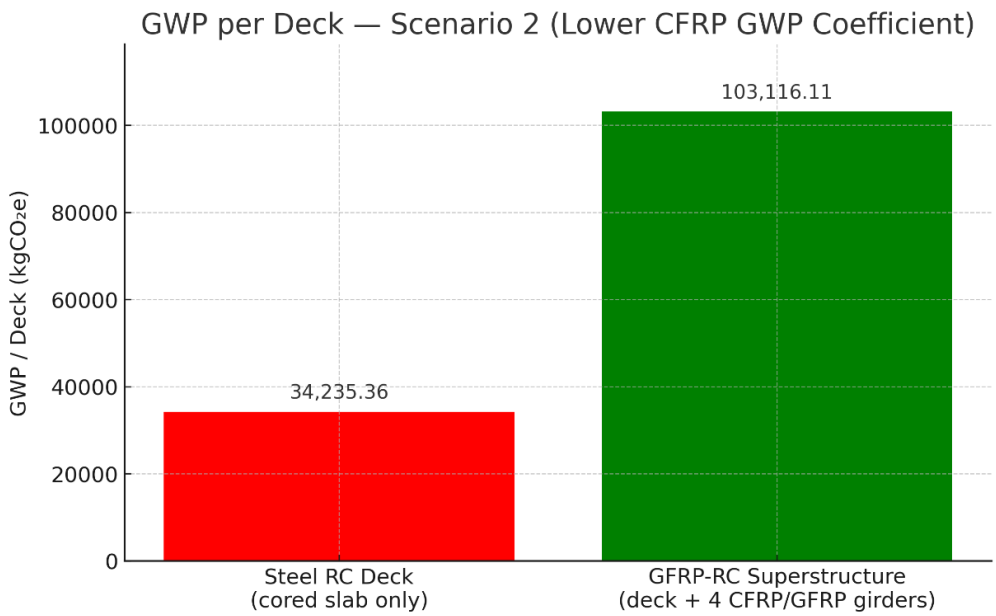


Figure 3.19:GWP per Deck-Scenario 2 (Steel-RC vs GFRP-RC)

Relative to the previous scenario (GFRP-RC = 116,930.91 kgCO_2eq), the FRP option drops by ~11.8%).The sensitivity to the CFRP emission factor is clear—lower CFRP intensity materially improves the FRP system's cradle-to-gate profile.

GWP/SPAN LENGTH: STEEL-RC vs GFRP -RC DECK

As shown in Figure 3.19, a lower CFRP coefficient cuts FRP GWP/Span from 3,836 → 3,383 kgCO_2eq (≈11.8%).

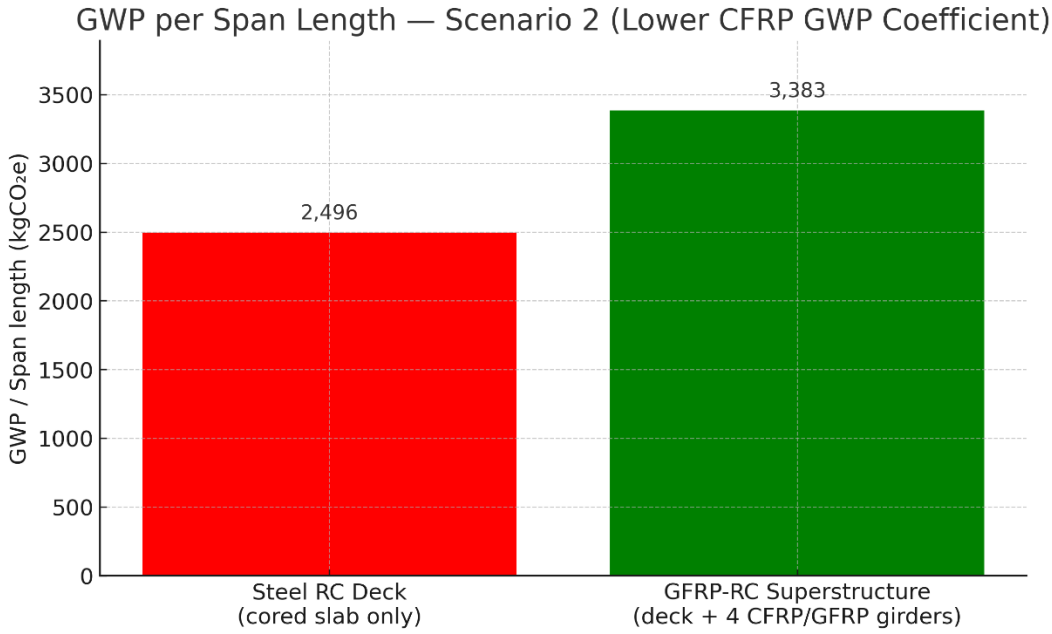


Figure 3.20:GWP/Span Length-Scenario2 (Steel-RC vs GFRP-RC)

With steel constant at 2,496 $kgCO_2eq$/span, the FRP–steel gap shrinks from 1,340 → 887 $kgCO_2eq$ (≈34% gap reduction). FRP remains ~35.6% higher than steel per span (down from ~53.7% in Scenario 1), reflecting that FRP's scope includes deck + four girders and greater delivered capacity, while reduced CFRP intensity materially improves FRP's per-span profile.

GWP/100 YEARS PER DECK: STEEL-RC vs GFRP -RC

Lastly, a 100-year reference service life scenario was considered by combining the initial cradle-to-gate (A1–A3) GWP with estimated maintenance-related contributions as shown in Table 3.31.

Table 3.32:GWP/100 RSL (Steel-RC vs GFRP-RC Deck)

	GWP/Deck ($kgCO_2$ eq)	**At 100 years RSL**	**(+)12%**	**GWP/100 years**
Existing Bridge (Steel-RC)	34235.36	(**x2**)68470.73	+4108.24	**72578.97**
New Bridge (GFRP-RC)	103 116.11	0	0	**103 116.11**

Steel-RC Deck (per 100 years):

Initial GWP (A1–A3): 68,470.73 $kgCO_2eq$

(12%) Maintenance GWP: 4,108.24 $kgCO_2eq$

Total GWP over 100 years:

$$GWP\ Steel = 68{,}470.73 + 4{,}108.24 = 72{,}578.97\ kgCO_2eq \tag{1.2}$$

GFRP-RC Deck (per 100 years):

One-time total GWP (A1–A3): 55,973.79 $kgCO_2eq$

Maintenance GWP: Assumed negligible

$$GWP\ GFRP = 103\ 116.11\ kgCO_2eq \tag{1.2}$$

Break-Even Point Calculation:

Assuming linear accumulation of GWP for the steel-RC deck and comparing it against the fixed GFRP GWP:

Annual GWP rate for Steel-RC:

$$\frac{72{,}578.97}{100} = 725.79\ kgCO_2eq/year \tag{1.3}$$

Set equal to GFRP's total:

$$725.79x = 103\ 116.11 \tag{1.4}$$

$$x = \frac{103\ 116.11}{725.79} \cong 142\ years \tag{1.5}$$

Utilizing (33% of A1-A3) maintenance GWP of Steel-RC Deck over a 100-service life suggested by [40], the break-even point occurs at ≅ 129 years.

GWP/100 YEAR/SPAN LENGTH: STEEL-RC vs GFRP -RC DECK

Table 3.32 shows the GWP over 100 years normalized per Span Length of each corresponding Deck.

Table 3.33:GWP/100 Year/Span Length (Steel-RC vs GFRP-RC Deck)

	GWP/100 years	GWP/100years/Span Length
Existing Bridge (Steel-RC)	**72578.97**	**5290**
New Bridge (GFRP-RC)	**103 116.11**	**3383**

Figure 3.20 shows that a lower CFRP coefficient lowers FRP GWP/100 years per span length from 3,836 → 3,383 $kgCO_2eq$ (≈11.8%), consistent with the A1–A3 deck reduction and confirming high sensitivity to CFRP intensity.

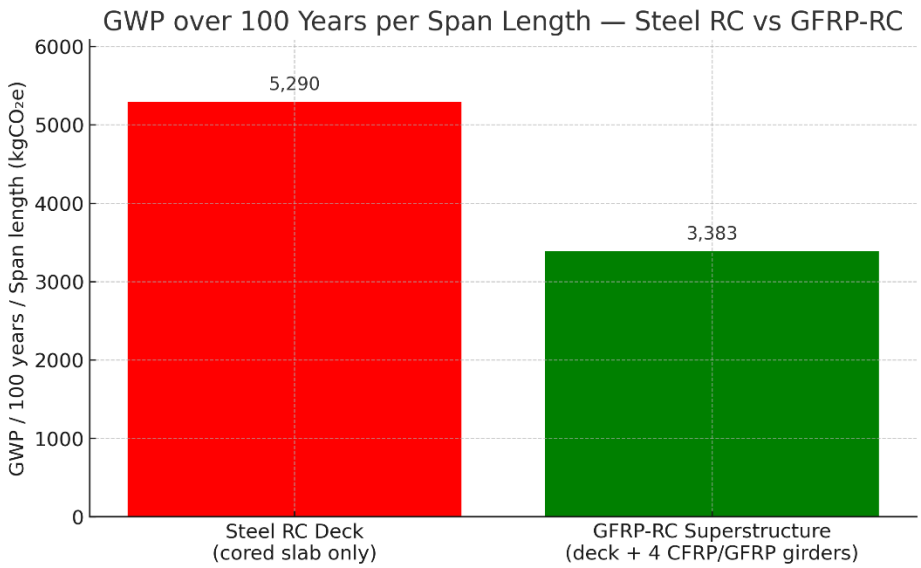


Figure 3.21:GWP/100 Year/Span Length-Scenario 2(Steel-RC vs GFRP-RC Deck)

With steel constant at 5,290 $kgCO_2eq/m$ (100-yr), under Scenario 2, FRP is 1,907 $kgCO_2eq/m$ lower (≈36% less). This metric is decision-relevant because it expresses the century-scale embodied carbon per metre of bridge delivered, simultaneously reflecting FRP's longer span count reduction and steel's maintenance/replacement burden.

3.5.4. Structural Element # 2: Pile (Steel-RC vs CFRP-RC)

Table 3.33 shows the GWP per pile, per moment capacity and per unit length at the A1–A3 product stage—i.e., emissions from raw material extraction, transport, and manufacturing—for two pile types used in coastal bridges in North Carolina. The existing pile, reinforced with high-strength steel strands and #7 gage steel wire, while the new replacement pile, constructed using CFRP strands for both longitudinal and transverse reinforcement.

As stated earlier during the Deck-GWP analysis, owing to a range of the GWP of CFRP from literature [23], 2 scenarios were utilized in this analysis, scenario 1:with CFRP, having a GWP coefficient of 28 888.80kgCO_2eq/m^3 and scenario 2(best case scenario): GWP coefficient of 14771.3 kgCO_2eq/m^3.

a) SCENARIO 1: CFRP AT 28 888.80 kgCO_2eq/m^3

Table 3.34: GWP/Pile Metrics-Scenario 1

SCENARIO 1:	**CFRP At 28888.80**	**kgCO_2 eq/m^3**		
	GWP/Pile (kgCO_2 eq)	**Moment Capacity(kNm)**	**GWP/Moment Capacity**	**GWP/Unit length**
Existing Bridge (Steel-RC)	**1824.84**	337.60	5.41	124.73
New Bridge (GFRP-RC)	**7225.08**	791.80	9.12	237.04

GWP/PILE AT INITIAL CONSTRUCTION: (STEEL-RC vs CFRP-RC)

Figure 3.21 presents a comparative analysis of GWP per pile at the A1–A3 product stage, for two pile types (Steel-RC vs CFRP-RC).

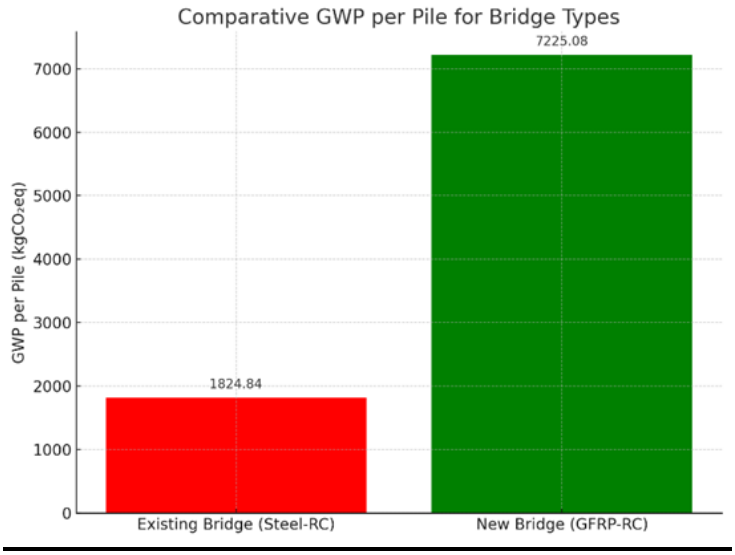


Figure 3.22: CFRP Pile Scenario 1 GWP/Initial Construction

The existing pile, reinforced with high-strength steel strands and #7 gage steel wire, shows a GWP of 1,824.84 kg CO_2eq, while the new replacement pile, constructed using CFRP strands for both longitudinal and transverse reinforcement, exhibits a significantly higher GWP of 7,225.08 kg CO_2eq, which is nearly four times greater than the steel alternative.

Steel-RC Pile (Existing Bridge):

The significantly lower initial GWP is attributable to the lower embodied carbon of steel strands (especially those produced via Electric Arc Furnace routes with high recycled content), efficient reinforcement use, as high-strength steel strands provide high tensile capacity per unit weight, and well-established, mass-optimized construction practices for steel RC piles.

However, this low upfront environmental cost comes at a performance trade-off. In marine environments, steel suffers from long-term corrosion [5] , particularly in piles subject to tidal exposure—resulting in section loss over time, increased maintenance needs (e.g., jacketing, cathodic protection), premature deterioration, which in this case necessitated full bridge replacement after only 50 years.

CFRP-RC Pile (New Bridge):

The much higher GWP at the A1–A3 stage results from the carbon-intensive nature of CFRP production, particularly carbon fiber synthesis, which involves energy-demanding processes such as polyacrylonitrile stabilization and graphitization at temperatures up to 2,000°C, the use

of thermoset resin systems (commonly epoxy or vinyl ester) with significant fossil-derived feedstocks [23], [24], compared to steel.

Despite the steep environmental cost of production, CFRP offers critical durability benefits including, its immunity to corrosion, especially in highly aggressive chloride-laden environments, minimal maintenance requirements, which over a 100-year design life can lead to major GWP savings in the use phase, and superior fatigue resistance and potential for lightweight structural design, further reducing system-wide impacts [23], [24].

GWP/MOMENT CAPACITY: (STEEL-RC vs CFRP-RC)

The Figure 3.22 compares the GWP per unit moment capacity (kg CO_2-eq/kNm) of bridge piles from the existing steel-reinforced bridge and the new CFRP-reinforced replacement bridge.

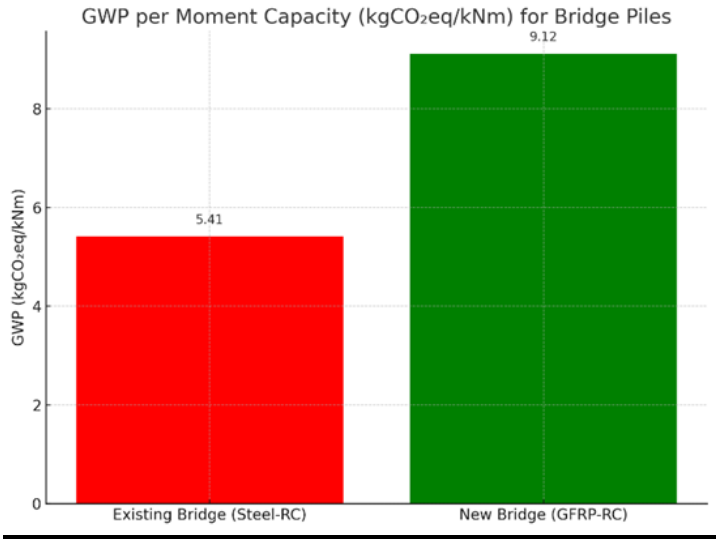


Figure 3.23:CFRP Pile Scenario 1 GWP/Moment Capacity

The steel-RC pile records a lower GWP per unit moment capacity of 5.41 kg CO_2eq/kNm, whereas the CFRP-RC pile exhibits a higher value of 9.12 kg CO_2eq/kNm, representing a 68% increase in carbon intensity per flexural strength delivered.

This performance-normalized metric reflects the climate efficiency of structural capacity—how much carbon is emitted to deliver a given moment resistance in bending, which is a critical performance parameter for deep foundations subjected to lateral and overturning loads (e.g., wave or vessel impact, scour exposure). The higher GWP/moment capacity for the

CFRP-RC pile can be attributed to:

High embodied carbon in CFRP (especially carbon fibers and epoxy resins), which dominates the A1–A3 impact, potential conservative design allowances for newer materials lacking long-term field data, possibly leading to over-reinforcement or higher safety factors.
Conversely, steel strands offer high tensile strength and modulus, enabling efficient moment capacity with less material, explaining the lower GWP per unit capacity.
While CFRP shows higher GWP per kNm of capacity, this result does not capture the benefits of extended durability. In marine pile applications, corrosion-related degradation significantly reduces steel pile performance over time, often necessitating section repair or jacketing, load capacity reductions and earlier replacement.

In contrast, CFRP-RC piles maintain moment capacity over time due to corrosion immunity, leading to a more stable long-term structural and environmental profile. At the A1–A3 stage, steel-reinforced piles are more carbon-efficient per unit moment capacity than CFRP-reinforced piles. While CFRP piles are structurally and environmentally costlier upfront, their long-term structural integrity and corrosion resistance justify their use in applications where reliability over a 100-year horizon is critical.

GWP/UNIT LENGTH: (STEEL-RC vs CFRP-RC)

Figure 3.23 compares the GWP per unit length (kg CO_2eq/m) for the bridge piles of the existing steel-reinforced bridge and the new FRP-reinforced bridge.

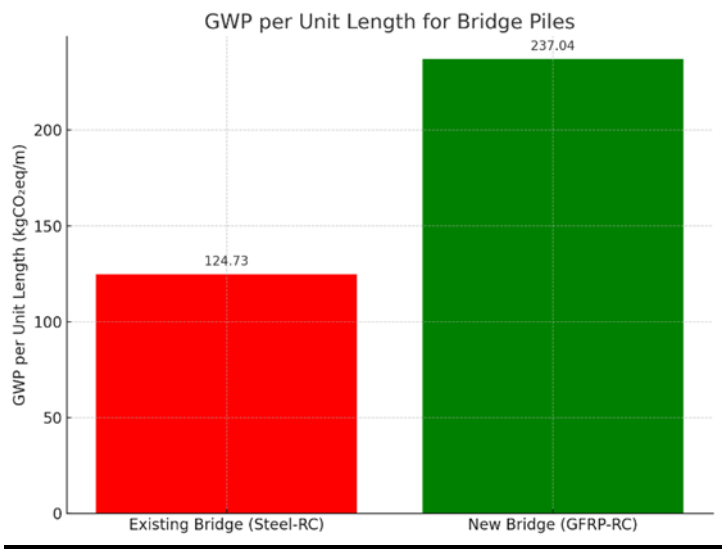


Figure 3.24:CFRP Pile Scenario 1 GWP/Unit Length

The steel-RC pile exhibits a GWP of 124.73 kg CO_2eq/m, while the CFRP-RC pile shows a markedly higher value of 237.04 kg CO_2eq/m, reflecting a 90% increase in embodied carbon per meter of pile length at the A1–A3 stage. This metric isolates the environmental intensity per linear meter of pile construction, offering insight into how material choices and section design affect environmental impact over the structural footprint.

Steel-RC Pile:

Achieves a lower GWP/m primarily due to lower embodied carbon per kg of steel reinforcement, efficient cross-sectional design enabled by steel's high modulus of elasticity (~200 GPa) and well-established design optimization, compact reinforcement cages, minimizing concrete volume and associated emissions per meter.

CFRP-RC Pile:

The higher GWP/m results from the high embodied energy of CFRP reinforcement, particularly carbon fiber and resin production, a likely increase in reinforcement quantity and cross-sectional concrete volume to satisfy serviceability and stiffness criteria, as CFRP has a lower modulus (~150 GPa) and different bond behavior compared to steel, more conservative design assumptions, as CFRP is still an emerging material in deep foundation applications.

Although CFRP offers superior durability, its environmental efficiency per meter is lower at the product stage. This matters especially when pile count or total length is extensive—as is often the case in marine and soft-soil environments. From a design perspective: Engineers may need to increase pile diameter or reinforcement area to maintain structural capacity and serviceability with CFRP, these adaptations directly translate into higher material usage per meter, thereby increasing GWP.

3.5.5. GWP/100 Years Per Pile: Steel-RC vs CFRP -RC

The Table 3.34 presents the 100-year GWP of bridge piles from the existing steel-RC bridge and the new GFRP-RC bridge, incorporating both initial A1–A3 emissions and assumed lifecycle maintenance impacts [32], which applies for the piles as well considering that the 12% is the operations and use stage GWP contribution in the lifecycle stage of steel-RC structures

in coastal regions on the assumption that superstructure replacement simultaneously means pile replacement.

Table 3.35:GWP/100 RSL Piles (Steel vs CFRP)

	GWP/Pile(kgCO2eq)	At 100 years RSL	(+)12%	GWP/100 years
Existing Bridge (Steel-RC)	1824.84	**(x2)**3649.68	**(+)**218.98	**3868.67**
New Bridge (CFRP-RC)	7225.08	0.00	0.00	**7225.08**

Figure 3.24 presents the 100-year GWP comparison of bridge piles.

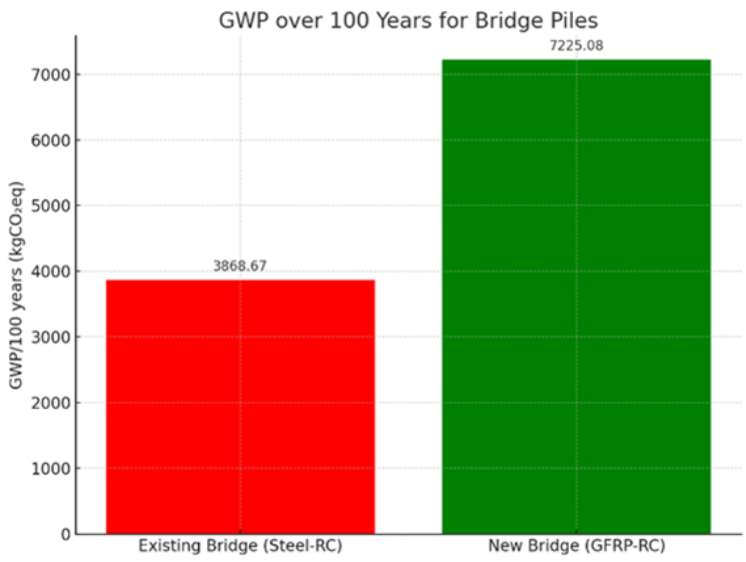


Figure 3.25:CFRP Pile Scenario 1 GWP/100 RSL

The steel-reinforced pile, with an initial GWP of 3,868.67 kg CO_2eq, includes an added 12% maintenance-related GWP, based on coastal durability studies such as [32].The CFRP-reinforced pile, with a GWP of 7,225.08 kg CO_2-eq, assumes negligible maintenance needs, justified by the corrosion immunity and long-term durability of CFRP in marine conditions.

Despite the CFRP-RC pile having nearly double the GWP of the steel-RC pile over 100 years, this differential is strictly front-loaded. The steel pile's GWP will continue to accumulate with time due to corrosion-induced degradation, repair activities (e.g., jacketing, protective coatings), and structural deficiencies that may arise before reaching the 100-year design life.

In contrast, CFRP-RC piles offer passive durability, with no expected structural degradation or intervention over the full design life.

Steel-RC Pile (Per 50 Years):

Initial GWP (A1–A3): 1,824.84 $kgCO_2eq$
Maintenance GWP: 109.49 $kgCO_2eq$ (6% of A1–A3)
Total per 50 years:

$$GWPSteel,\ 50y = 1{,}824.84 + 109.49 = 1{,}934.33\ kgCO_2eq \quad (1.6)$$

CFRP-RC Pile:
One-time GWP (A1–A3): 7,225.08 $kgCO_2eq$
Maintenance GWP: 0 (assumed negligible)
Total per 100 years:

$$GWP\ CFRP,\ 100y = 7{,}225.08\ kgCO_2eq \quad (1.7)$$

Steel-RC GWP Accumulation Over Time:
The Steel-RC pile has a 50-year service life, so its GWP will repeat every 50 years due to full replacement. Table 3.35 shows the steel-RC GWP Accumulation Over Time.

Table 3.36:Steel-RC GWP Accumulation Over Time

Time (years)	GWP ($kgCO_2eq$)
0-50	1,934.33
50-100	2 × 1,934.33 = 3,868.66
100-150	3 × 1,934.33 = 5,802.99
150-200	4 × 1,934.33 = 7,737.32

Break-Even Point
Now, calculating the exact time (X) when the cumulative GWP of the steel-RC pile equals that of the CFRP pile:
Let:

$$GWP\ Steel(X) = \left(\frac{1{,}934.33}{50}\right) \times X = 38.69 \times X \quad (1.8)$$

Set equal to CFRP GWP:

$$38.69X = 7{,}225.08 \tag{1.9}$$

$$X = \frac{7{,}225.08}{38.69} \cong 186.7\ years \tag{2.0}$$

Considering that steel-RC pile has a 50-year service life, with maintenance GWP of 109.49 $kgCO_2eq$ per cycle, the cumulative GWP equals that of the CFRP pile at approximately 187 years. This means that steel-RC piles remain more carbon-efficient over shorter lifespans (≤150 years), assuming full replacement cycles. Assuming a 75-year service life for the steel-RC pile, the cumulative GWP equals that of the CFRP pile at ≅ 280 years.

However, CFRP piles become environmentally favorable over very long service horizons (≥187 years). Importantly, the superior durability and maintenance-free nature of CFRP still offer performance and cost-related advantages, especially in marine environments where corrosion can accelerate degradation unpredictably. Thus, from both an engineering resilience and a carbon lifecycle perspective, CFRP piles remain a long-term sustainability strategy, particularly for critical infrastructure in aggressive exposure zones.

GWP/100 YEAR/UNIT LENGTH: STEEL-RC vs GFRP -RC PILE

Table 3.37 shows the GWP over 100 years normalized per Unit Length of each corresponding Pile.

Table 3.37:GWP/100 Year/Unit Length (Steel-RC vs GFRP-RC Pile)

	GWP/100 years	GWP/100years/Unit Length
Existing Bridge (Steel-RC)	**3868.67**	**264**
New Bridge (GFRP-RC)	**7225.08**	**237**

As shown in Figure 3.25, over a 100-year reference life, the steel RC pile (prestressing strands + #7 wire) has 264 $kgCO_2e/m$, while the CFRP-RC pile (CFRP strands) posts 237 $kgCO_2e/m$, a ~10.2% reduction per metre.

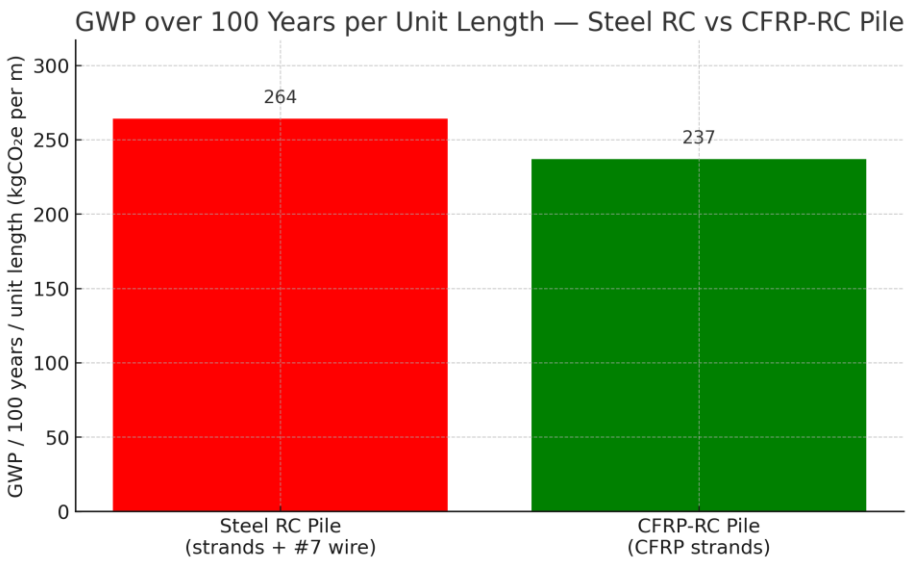


Figure 3.26: GWP/100 Years/Unit Length-Scenario 1(Steel-RC vs CFRP-RC)

Although the total 100-year GWP per pile is higher for CFRP (7,225 vs 3,869 $kgCO_2eq$) due to system scope and material factors, the unit-length normalization isolates carbon intensity of the linear element itself and indicates greater life-cycle carbon efficiency per metre for the CFRP solution. This metric is relevant for layout/design decisions because it removes effects of pile length/count and expresses the embodied carbon required to deliver one metre of foundation over a century—supporting CFRP where durability and corrosion immunity translate into lower per-metre climate burden.

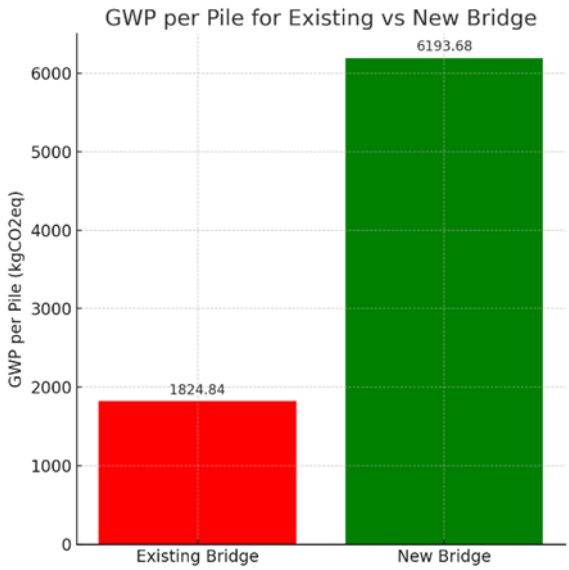
b) SCENARIO 2: CFRP AT 14771.3 $kgCO_2eq/m^3$

The Table 3.36 shows the GWP per pile, per moment capacity and per unit length at the A1–A3 product stage under when scenario 2 of GWP:14,771.3 $kgCO_2eq/m^3$ is considered.

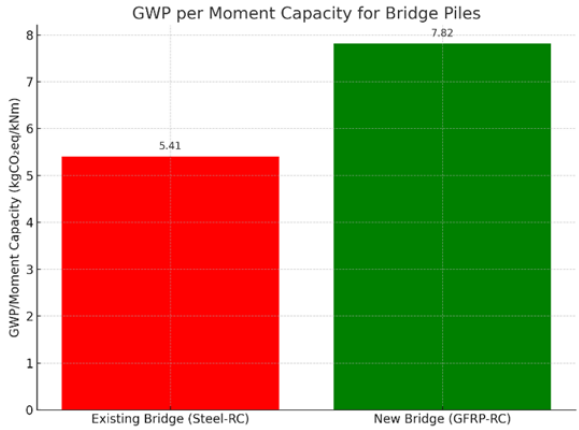
Table 3.37: GWP/Pile Metrics-Scenario 2

SCENARIO 2:	**CFRP At 14771.3**	**$kgCO_2eq/m^3$**		
	GWP/Pile($kgCO_2$ eq)	**Moment Capacity(kNm)**	**GWP/Moment Capacity**	**GWP/Unit length**
Existing Bridge (Steel-RC)	**1824.84**	337.60	5.41	124.73
New Bridge (CFRP-RC)	**6193.68**	791.80	7.82	203.20

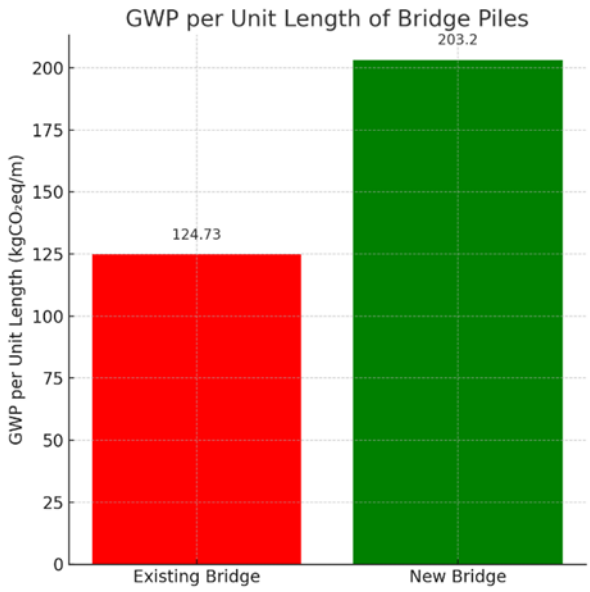
Figure 3.26 shows CFRP Pile Scenario 2 Comparative Metrics(a) GWP/Pile, (b)GWP/Moment Capacity, (c)GWP/Unit length vs Steel-RC Piles.



(a) GWP/Pile initial construction



(b)GWP/Moment Capacity



(c)GWP/Unit length

Figure 3.27:CFRP Pile Scenario 2 Comparative Metrics(a) GWP/Pile, (b)GWP/Moment Capacity, (c)GWP/Unit length

The presented Scenario 2 results reflected the impact of using a revised, lower GWP value for CFRP strands—14,771.3 $kgCO_2eq/m^3$ (vs. 28,888.80 $kgCO_2eq/m^3$ in Scenario 1). This adjustment resulted in a significantly improved environmental performance for the CFRP-reinforced pile, across all metrics. The reduction in CFRP strand GWP (from 28,888.80 to 14,771.3 $kgCO_2eq/m^3$) leads to a ~49% drop in the reinforcement's environmental burden, resulting in more favorable overall performance.

While CFRP-RC piles still show higher GWP than steel-RC, the magnitude of difference is substantially narrowed across all metrics:

- GWP per pile is reduced by over 3,000 kg CO_2eq.
- GWP per moment capacity and per unit length now reflected smaller trade-offs in exchange for significant gains in durability and corrosion resistance.

GWP/moment capacity, a functionally normalized metric, now highlighted only a ~45% increase compared to steel, strengthening the justification for CFRP in performance-critical applications.

Under Scenario 2, the use of an updated, lower GWP value for CFRP strands significantly improves the environmental efficiency of CFRP-RC piles. While steel-RC remains more carbon-efficient at the A1–A3 stage, the reduced gap in GWP performance, especially when

normalized by capacity or length, enhances the viability of CFRP as a structurally robust, lifecycle-optimized solution for marine substructures. This scenario illustrates how material innovation and cleaner CFRP manufacturing can substantially improve the sustainability profile of FRP-based infrastructure.

Break-Even Point when considering Scenario 2 occurs at

$$\cong 160\ years$$

A significant reduction of about 27 years. Considering a service life of 75 years for the steel-RC pile, the cumulative GWP breaks even at ≅ 240 years.

4. CONCLUSIONS AND FURTHER DEVELOPMENTS

4.1. Main Conclusions

This thesis evaluated the embodied-carbon performance of steel and FRP reinforcement systems for concrete bridges from the product stage (A1–A3) through construction (A4–A5) to structural, function-based normalizations and 100-year reference-service-life comparisons. Across scales—from material (rebar) to elements (deck, piles, girders) to the full bridge context—three consistent insights emerge.

1) Mass-based results favour steel; performance-based results frequently favour FRP.

At the declared unit level (per metric ton), steel rebars exhibit markedly lower A1–A3 GWP (≈480–850 kg CO_2eq/ton) than GFRP rebars (>2,300 kg CO_2eq/ton), reflecting the energy and feedstock intensity of resin synthesis and glass fibre production, alongside regional electricity mixes [30]. Per-meter results for 10 mm bars similarly favour steel (≈0.26–0.35 vs 0.39–0.56 kg CO_2eq/m), driven by steel's Electric Arc Furnace routes and high scrap content [1]. However, when impacts are normalized by tensile capacity (kg CO_2eq/MPa), GFRP products outperform steel (≈3.9–4.3 × 10^{-4} vs 5.3–6.7 × 10^{-4} kg CO_2eq/MPa), revealing higher carbon efficiency per unit mechanical utility for GFRP owing to its high ultimate strength and low density [10], [19], [30]. A density-to-strength perspective reinforces this pattern: steel's high density and moderate yield strength produce much larger D/S ratios than GFRP, so even with higher GWP per ton (≈2,270–3,360 kg CO_2eq/ton for GFRP), the strength delivered per unit embodied carbon improves in GFRP when function is considered [13], [29].

2) Construction-stage realities (A4–A5) amplify FRP's logistics advantages but require procedural care.

Interviews and case experience indicate that GFRP's low density reduces truck trips and handling energy at A4, while A5 benefits include easier cutting and safer, spark-free work, often improving installation productivity (~20%)—albeit with strict handling, UV-protected storage, tailored supports, and pre-bending logistics [14], [31]. Steel retains advantages in on-

site flexibility (bending, welding, splicing) and supply chain maturity. These complementary findings confirm that A4–A5 differences are material and context dependent, but they do not overturn the A1–A3 hierarchy; rather, they narrow it for GFRP through transport and constructability gains.

3) Over a 100-year horizon, durability governs carbon outcomes

When results were normalized to functional performance and service life, a different trend emerged. The FRP bridge deck, despite its higher initial footprint, enabled longer spans (30.48 m vs 13.72 m), reducing pier and substructure requirements per kilometre of crossing. Over a 100-year reference life, the FRP system demonstrated a ~27–36% lower GWP per metre of bridge delivered compared to steel, once span length and maintenance requirements were considered. For piles, while CFRP reinforcement increased A1–A3 emissions, the 100-year length-normalized impact showed a ~10% reduction compared to steel, reflecting CFRP's corrosion immunity and negligible maintenance demand in marine exposure conditions.
A further sensitivity analysis highlighted that the results are highly dependent on the assumed carbon intensity of CFRP manufacturing. Using a lower GWP coefficient for CFRP strands improved the environmental profile of FRP systems substantially, narrowing the gap at the product stage and strengthening their advantage at the whole-life level. This demonstrates that decarbonization of CFRP production processes represents a key pathway to enhancing the sustainability of FRP-reinforced infrastructure.

Contributions and implications.
Collectively, the work (i) demonstrates that mass-based LCA alone inaccurately ranks reinforcement options, while performance-based and bridge-level normalizations (per MPa, per kNm, per span) reveal contexts where FRP is competitively (or superiorly) carbon-efficient; (ii) quantifies durability-driven carbon avoidance, showing explicit deck-level break-even timing and pile-level conditions under which FRP overtakes steel; (iii) integrates construction-stage practice to capture transport and installation realities; and (iv) establishes scenario-sensitivity to upstream CFRP emission factors, directly linking supply-chain decarbonization to project-level carbon decisions. For coastal bridges, the overall picture is nuanced: GFRP rebars can be the lower-carbon choice over long design lives for decks and long spans (due to maintenance avoidance and span efficiency), while CFRP piles require either cleaner fibre/resin

supply chains or credible expectations of early steel replacement to achieve life-cycle parity within 100 years.

Limitations and scope of validity.

Comparisons among EPDs carry program and dataset heterogeneity (ISO 14025 comparability caveats) and declared-unit results (per ton) are not decision-sufficient; functionally equivalent units must be used to avoid bias [13], [29], [30]. Structural results are design-specific—serviceability criteria (modulus, crack control, cover) and detailing requirements materially affect quantities, and thus A1–A3 outcomes [7], [33]. The maintenance assumptions (12% over 100 years for coastal steel, negligible for FRP) are evidence-informed but still assumptions; site exposure, inspection regimes, and owner standards can shift them [29]. Finally, the CFRP GWP range is a major uncertainty driver; the scenario analysis confirms that upstream decarbonization (electricity mix, precursor chemistry, cure strategies) meaningfully changes conclusions for FRP elements [18], [19], [30].

4.1.1. Recommendations

1) Adopt performance-based environmental benchmarking in reinforcement selection.

Decision-making for bridge reinforcement should move beyond mass-based GWP metrics toward functionally normalized comparisons (e.g., kg CO_2-eq/MPa, kg CO_2-eq/kNm, kg CO_2-eq/m of span) [13], [29], [30]. These metrics better capture the structural efficiency of low-density, high-strength materials like GFRP and CFRP, especially in marine environments where corrosion immunity influences long-term performance. For procurement specifications, agencies should mandate LCA reporting per functional unit, harmonized with ISO 14044 principles, to ensure fair and technically relevant comparisons.

2) Integrate durability-driven lifecycle modelling into design standards.

Service life modelling should be embedded into structural design codes for marine and de-icing salt environments, with explicit environmental performance outputs alongside cost and structural safety checks [7], [33]. For example, AASHTO and ACI provisions could incorporate carbon break-even timelines as a decision-support metric, similar to cost-benefit timelines, to account for maintenance-related carbon accumulation in steel RC versus maintenance-free FRP RC.

3) Prioritize FRP in applications with high maintenance access cost and aggressive exposure.

GFRP rebars should be prioritized for bridge decks, long-span girders, and substructures in splash/tidal zones where chloride-induced corrosion is severe, maintenance access is difficult (overwater, high-traffic), and disruption costs are high [14], [29]. In such cases, the carbon premium at A1–A3 can be offset well within the service life. CFRP strands, despite their higher embodied carbon, remain viable for high-fatigue, deep-foundation, and seismic-critical piles where structural reliability and zero corrosion tolerance are paramount—especially when paired with lower-GWP CFRP manufacturing routes.

4) Advance FRP supply-chain decarbonization.

The scenario analysis demonstrated that halving CFRP strand GWP (through cleaner electricity, precursor optimization, and resin formulation changes) reduced pile and girder A1–A3 emissions by up to ~49%, bringing FRP closer to steel in per-capacity metrics. Industry R&D should focus on:

- Renewable-powered fiber production (electrified furnaces, waste heat recovery)
- Low-carbon resin systems (bio-based epoxies, recyclable thermoplastics)
- Optimized fiber-resin ratios to reduce resin volume without compromising performance.

5) Improve constructability and adaptability of FRP reinforcement.

While GFRP offers transport and handling advantages, its installation requires pre-bending, UV-protected storage, and specialized handling tools [14], [31]. Industry-standard modular bending and coupler systems should be developed to improve on-site adaptability and reduce schedule risk. Pre-approved vendor lists, prequalification testing, and just-in-time delivery logistics can mitigate procurement delays observed in the Harkers Island case study (USA).

6) Develop hybrid reinforcement strategies.

Hybrid systems combining steel and FRP (e.g., GFRP for corrosion zones, steel elsewhere) could optimize both cost and environmental performance. Such strategies may delay FRP's environmental break-even point relative to full-FRP solutions but can offer incremental decarbonization with reduced upfront cost and supply-chain burden.

7) Standardize long-term monitoring and environmental reporting.

To validate LCA assumptions, bridge projects using FRP should incorporate in-situ performance monitoring over decades, capturing deflection, crack width, environmental exposure, and lifecycle maintenance events. This would provide high-quality field data to refine service life models and carbon break-even calculations, reducing uncertainty in durability assumptions [4], [29].

4.1.2. Further Developments

To advance the environmental assessment of FRP-reinforced concrete, future studies should address several key areas:

Lifecycle Completion (Use and End-of-Life Stages):

Quantify emissions from maintenance (B2–B5), traffic impacts during interventions (B6), and disposal/recycling potential for steel and FRP (C3–D), which were not covered in the current study due to data limitations.

Diversification of FRP Types Design for Deconstruction and Recycling:

Assess the environmental performance of alternative FRP materials such as Basalt FRP (BFRP), Aramid FRP (AFRP), and hybrid composites like glass-carbon blends, which may offer lower embodied carbon or balanced mechanical benefits. Investigate recyclable FRP systems, especially thermoplastic FRPs, to improve end-of-life sustainability and promote circularity in structural applications.

System-Level Structural Analysis:

Extend analysis beyond reinforcement to full bridge typologies (e.g., precast vs cast-in-place) to capture system-level GWP variations driven by design and construction methods.

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