Life Cycle Cost and Life Cycle Assessment Analysis at the Design Stage of a Fiber Reinforced Polymer Reinforced Concrete Bridge in Florida

Thomas Cadenazzi[1*], Giovanni Dotelli[2], Marco Rossini[1], Steven Nolan[3] and Antonio Nanni[1]

ABSTRACT

To support and promote the deployment of innovative technologies in infrastructure, it is fundamental to quantify their implications in terms of both economic and environmental impacts. Glass Fiber-Reinforced Polymer (GFRP) bars and Carbon Fiber-Reinforced Polymer (CFRP) strands are validated corrosion-resistant solutions for Reinforced Concrete (RC) and Prestressed Concrete (PC) structures. Studies on the performances of FRP reinforcement in seawater and salt-contaminated concrete have been conducted and show that the technology is a viable solution. Nevertheless, the economic and environmental implications of FRP-RC/PC deployment have not been fully investigated. This paper deals with the Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) analyses of an FRP-RC/PC bridge in Florida. The bridge is designed to be entirely reinforced with FRP bars and strands and does not include any Carbon Steel (CS) reinforcement. Furthermore, the deployment of seawater concrete in some of the elements of the bridge is considered. LCC and LCA analyses at the design stage are performed. Data regarding equipment, labor rates, consumables, fuel consumption and disposal were collected during the construction phase and the analysis is refined accordingly. The FRP-RC/PC bridge design is

---

[1] Department of Civil, Arch. and Environ. Engineering, University of Miami, Coral Gables, FL
[*] txc470@miami.edu
[2] Department of Chemistry, Materials and Chemical Engineering, Politecnico di Milano, Milano, Italy
[3] State Structures Design Office, Florida Department of Transportation, Tallahassee, FL

compared to a traditional CS-RC/PC alternative. Salient differences are discussed to determine the least impacting solution from both an economic and environmental perspective.

Keywords

Fiber reinforced polymer, reinforced concrete, prestressed concrete, bridges, life-cycle cost, life-cycle assessment, sustainable constructions.

Introduction

Composite materials are finding their way into bridge construction. Namely, Glass Fiber Reinforced Polymers (GFRP) bars and Carbon Fiber Reinforced Polymer (CFRP) strands are promising technologies for the design of durable, low-maintenance Reinforced Concrete (RC) and Prestressed Concrete (PC) structures [1]. Thanks to their corrosion resistance, FRP bars and strands are effective alternatives to carbon steel (CS) reinforcement in marine and coastal environments where corrosion can affect specific elements of the substructure [2]. FRP reinforcement has acquired favorable reception among contractors thanks to its reduced weight that can result in safer operations, allowing for easier handling on-site, faster installation, and reduced need for heavy equipment [3]. FRP bars and strands have different material properties with respect to traditional CS counterparts: they are elastic until failure, stronger, but less stiff. These differences need to be accounted for during design [4].

A major factor that may contribute to foster the deployment of FRP bars and strands in construction is represented by their positive economic and environmental implications. However, the lack of rigorous research based on specific case studies makes it difficult for practitioners and owners to fully understand the potential of FRP reinforcement. In this research, a deterministic-based method is applied to the Life-Cycle Cost (LCC) and Life-Cycle Assessment (LCA) analyses of a specific FRP-RC/PC bridge that has been selected as a case study. The selected case study is an FRP-RC/PC short-spanned vehicular bridge named the Halls River Bridge (HRB). The structure is located in Homosassa, Florida. The performance of the structure is compared to that of a traditional CS-RC/PC alternative.

The FRP-RC/PC bridge is designed for a service life of 100 years in accordance with the emerging state-of-the-practice for FRP reinforcement [5]. The CS-RC/PC alternative is designed for a service life of 75 years in accordance with the current practice in the US [6].

The LCC and LCA analyses are performed over a 100-year reference period and include: material fabrication, construction, use and maintenance, and end of life. At the end of its 75-year service life the CS-RC/PC is reconstructed to reach the 100-year goal. A portion of the reconstruction cost and environmental impact is included in the analyses, along with the additional maintenance occurring until the 100-year goal is reached. The discount rate is identified as a sensitive parameter affecting the LCC. Thus, a parametric analysis is carried out to quantify its influence. This study wants to serve as guideline for the analysis of FRP-RC/PC infrastructural applications.

Bridge Structure

The Halls River Bridge (HRB) is a short-spanned vehicular bridge located in Homosassa, Florida. The bridge is part of a replacement project for an existing structure that reached functional deficiency and aged beyond its service life. The new structure comprises five spans for a total length of 56.7 m and a width of 17.6 m. It serves as the only passageway over the Halls River for the community of Homosassa Springs. The water way is tidally affected by seawater contamination, particularly during storms, given the proximity to the Gulf of Mexico.

Given its exposure conditions and structural configuration, the HRB was selected to serve as demonstrator for both the SEACON-Infravation research project [7] and the Florida Department of Transportation (FDOT) Transport Innovation Challenge (TIC). One of the aims of the latter is to leverage the deployment of non-corrosive technologies in transportation infrastructure.

The HRB FRP-RC/PC design comprises a number of innovative material and structural solutions targeting a reduced environmental impact and an extended service life of 100 years. Details on the design of the HRB are discussed by Rossini et al. [7]. The structure includes 36 CFRP-PC bearing piles, 235 CFRP-PC/GFRP-RC sheet piles, 6 GFRP-RC bent caps and bulkhead caps, a 998 m^2 GFRP-RC bridge deck, 150 m long GFRP-RC traffic railings, two 161 m^2 GFRP-RC approach slabs and a 20 m long GFRP-RC gravity wall. The original design implemented Hillman Composite Beams (HCB), consisting of a composite GFRP shell encasing a steel-reinforced concrete shallow tied-arch and lightweight filling foam [8]. This complex structural solution was developed under the National Cooperative Highway Research Program's Innovations Deserving Exploratory Analysis (NCHRP-IDEA) program and selected by FDOT for further exploration. An alternative GFRP-RC solution that provides equivalent strength and performance is considered in this study.

In addition to innovative reinforcement solutions, the FRP-RC/PC design features the deployment of sustainable concrete mixes in the elements of the substructure. Concrete mixed with seawater is used for the bulkhead cap, concrete with Recycled Concrete Aggregates (RCA) and concrete with Recycled Asphalt Pavement (RAP) aggregates is used for the GFRP-RC gravity walls. For investigation of enhanced night-time and wet weather visibility, white cement concrete and another mixture of high-content slag and fly ash are used in the GFRP-RC traffic railings. Figure 1a shows the substructure of the HRB before the installation of the superstructures. Figure

1b shows the north side of the HRB after completion.

The CS-RC/PC alternative is designed to provide equivalent strength and performance with respect to the FRP-RC/PC design. The main difference is in the required amount of reinforcement as a consequence of the different mechanical properties of FRP bars and strands compared to CS reinforcement. Each element maintains the same geometry except for the bearing piles. The section of the square CS-PC piles is increased to 0.61 meters to allocate a concrete clear cover of 76 mm for corrosion mitigation purposes as required by FDOT [9]. Similarly, the concrete mix used for the substructure of the CS-RC/PC alternative is required to include a percentage of silica fume to mitigate chloride penetration and consequent corrosion phenomena. This is not required when FRP reinforcement is used. Table 1 summarizes the FRP-to-CS reinforcement ratios for each member of the bridge. These ratios are conservative and tend to overestimate the amount of FRP reinforcement required. The design of GFRP-RC elements is expected to become more efficient following the publication of the second edition of AASHTO Bridge Design Specifications for GFRP Reinforced Concrete, approved in June 2018 [10]. Similarly, the design of CFRP-PC elements is expected to become more efficient following the publication of specific AASHTO design specifications, currently under development [11].

Bridge Inventory

Reference [12] discusses construction costs of bearing piles, sheet piles, bent caps, bulkhead caps, girders and deck of the HRB. In this study, three additional elements are introduced to complete and deepen the analysis: traffic railings, approach slabs, and gravity wall. Table 2 summarizes material quantities required for the construction of the FRP-RC/PC bridge and specifies whether each structural element is precast or cast-in-place (CIP). Table 3 summarizes suppliers and modes of transport for each element of the bridge. Time and distance covered from the manufacturer to the jobsite are also included.

Life Cycle Model

SERVICE LIFE AND DESIGN LIFE CONCEPT

As for AASHTO, 2017 [6] the service life is defined as the time-period during which the bridge structure provides the desired level of performance or functionality, with any required level of repair and maintenance. The bridge service life differs from the concept of design life, which is the period of time on which the statistical derivation of transient loads is based: 75 years for the current version of AASHTO [6]. The AASHTO specifications [6] do not currently define a specific service life in years for bridges. The definition of service life in the current version of AASHTO [6] is clearly not related to the design life or the probabilities associated with it. However, for most applications, it is reasonable for owners and designers to target a minimum service life of 75 years. In fact, recent researches [13] that deal with life cycle cost analyses of concrete bridges in corrosive environments and are based on preventive maintenance actions, use the 75-year period as service life. Such studies identify the 75-year period by averaging the service life reported from most DOTs in bridge projects that adopt CS as reinforcement [13]. As discussed in AASHTO, 2017 [6] to reach the expected service life, a systematic maintenance plan that includes the identification of “hot areas” requiring more detailed inspection and maintenance should be included in the analysis. On the other hand, the average age of the bridges in the U.S. is 42 years while they are designed for a service life of 75 years [14]. The large number of deficient bridges highlights the need for a better understanding of the effect of aggressive environments on their lifetime performance [14]. One of the main causes of deterioration of concrete structures in Florida is the chloride-induced corrosion of the reinforcement.

With the introduction of new durable non-corrosive materials, the expectation of industry is to guarantee a longer service life. Realizing a 100-year service life for bridges in aggressive environments requires a performance-based durability plan. However, a difficulty in using accelerated testing in predicting service life is the lack of long-term data on the in-service performance of concrete, as discussed in [4]. There are research studies that extrapolate behaviors up to 100 years and shall be intended as the best projections to date [15]. Additionally, [5] obtained experimental data and extrapolated it to determine a theoretical service life of 100 years [5]. Moreover, recent studies are showing that the degradation phenomena experienced by FRP may be less severe than shown in extrapolation from accelerated testing [16]. If this is the case, future practice may allow for the design of FRP-RC/PC structures for longer service lives at equivalent maintenance costs. Such observations and research studies are the factors taken into account in the model that paves the way for achieving a 100-year service life for FRP-RC/PC structures.

Based on the previous considerations, the authors of this research reasonably considered a service life of 75 years for the CS-RC/PC alternative, and a service life of 100 years for the FRP-RC/PC solution.

Different service life scenarios, and thus different end-of-life scenarios, can obviously change the analysis substantially. However, based on the current regulations and state of practice, the identified scenario is expected to be the most likely. For the purpose of comparing the two alternatives, for which a service life of 100-years is requested, the analysis of the CS-RC/PC bridge alternative takes into account one demolition and one reconstruction.

SYSTEM BOUNDARIES

The model implemented in this study builds on the procedure detailed in [17] and the same nomenclature is used. Adjustments are implemented to account for the peculiarities of a transportation infrastructure as discussed in the following. The life cycle of the GFRP-RC/PC alternative comprises four stages: 1) the product stage is subdivided in raw material supply (A1), transport of raw materials (A2), and manufacturing of intermediate products (A3); 2) the construction process stage includes transportation to the job site (A4), and construction and installation operations happening at the job site (A5); 3) the use stage includes user costs and environmental impacts (B1), maintenance (B2), repair (B3) and replacement of specific components (B4); and 4) End of Life (EoL) stage includes demolition (C1), transport of demolished material (C2), waste processing (C3), disposal (C4), and recycling (D).

The life cycle of the CS-RC/PC alternative comprises three supplementary stages in addition to the four already discussed. These are: 1) product stage for reconstruction (A1-A4 bis), 2) reconstruction process stage (A5 bis), and 3) use stage over the first 25 years of second life (B1-B4 bis). Only a portion of the costs and environmental impacts connected to reconstruction are included in the analyses. This accounts for the fact that only 25 years of the second life of the bridge will be exploited for the purposes of this comparison. Figure 2 shows the life cycle model assumed for the two design alternatives, and the corresponding boundary conditions.

MAINTENANCE AND REPAIR MODEL

The maintenance and repair model implemented in this study operates in preemptive maintenance. It allows to schedule systematic inspections and consequent repair activities before any incipient deterioration develops into a major damage. The maintenance model includes both routine activities and extraordinary intervention such as the replacement of specific elements or their Cathodic Protection (CP).

The maintenance and repair schedule is developed using the software Life-365 (version 2.2.3)

[18]. This tool provides a reliable database with information on chloride concentration across the US. Since HRB is located in Homosassa Bay, 109 km north of Tampa Bay, the same chloride concentration of 14 kg/m^3 can be assumed.

The chloride diffusion coefficient is a function of both time and temperature, and Life-365 uses the flowing formula (1) to account for time-dependent changes in diffusion [19]:

$$D(t) = D_{28}\left(\frac{t_{28}}{t}\right)^{m} \quad (1)$$

Where D(t) is the diffusion coefficient at time t, D_{28} is the diffusion coefficient at time t_{28}, set at 1.17E-8, and m is the diffusion decay index (based on the concrete mixture design detail), and set at 0.2 for Portland cement concrete, as suggested in the current version of Life-365. Additionally, the critical chloride threshold required to initiate corrosion of steel is set at 1.17 kg/m^3. These defaults values of Life-365 model were used to predict the maintenance schedule.

Figure 3 shows the periodical maintenance and repair activities scheduled for both alternatives. The FRP-RC/PC alternative requires only ordinary maintenance, whereas more significant intervention is required on the CS-RC/PC counterpart because of corrosion occurrence. The model accounts for the fact that the substructure elements are the most exposed and among the first ones to be installed. Thus, chloride penetration begins approximately one year before completion of the rest of the bridge. As a consequence, all the maintenance and repair occurrences are translated by one year.

Bearing Piles

Figure 4a shows the typical zones of corrosion for piles. HRB tidal zone is approximately 0.91 m, while splash zone counts for an additional 0.61 m as recorded during construction. Thus, the length of each pile to be repaired is 2.44 m. The repair solution for the piles consist of pile jacketing (Figure 4b). Pile jackets are externally applied to the damaged portion of the pile and contains a zinc wire mesh anode to apply cathodic protection from corrosion. Details are specified by FDOT Specifications Special Provision 457 [20]. Pile jackets are the most common type of pile protection in FDOT projects according to FDOT database.

With regards to the CS-RC/PC alternative, as per the model presented in Figure 3, the cathodic protection installation activities (indicated in Figure 3 as “CP”) take place periodically over the years of service. After 31 years cathodic protection is needed over 25% of the total number of bridge piles. This protection activity is indicated in Figure 3 as “CP1”. CP2 refers to the total number of bridge piles being protected for 50% at this stage, while CP3 accounts for the 75%. The remaining 25% of the total number of bridge piles is assumed to be repaired with conventional methods such as concrete patching. Given their service life of approximately 25 years, periodically, the cathodic protections are substituted. The time frame of each CP replaced is shown in Figure 3. At the end of their service life, CP are removed and replaced by new CP devices.

With regards to the FRP-RC/PC design, the scheduled maintenance operations consist of minor repairs to concrete taking place every 10 years. The patching activities for the FRP-RC/PC alternative are estimated at 33% of the CS-RC/PC design.

Sheet Piles and Bulkhead Cap

Sheet piles are flexural elements made collaborating through the casting of a bulkhead cap. RC and PC elements are subject to cracking. Cracking is not always an indication of structural problems, but the cracks provide an entry point for water and chlorides to penetrate and accelerate corrosion of reinforcing and prestressing steel. Cracking can occur in either the concrete cap or the sheet piles themselves. Crack repair is a common approach covered by FDOT specifications per FDOT sub article 400-21.5.2 [9]. In the model adopted, every 10 years the cracks on either the concrete cap or the concrete panels are supposed to be injected and sealed, along with flowable fill placed beneath the slope pavements at the bridge approaches. Since sheet piles usually tend to be obscured by water, marine growth or debris, most of wall inspections are performed from land. The model assumes that small cracks in sheet piles and bulkhead cap are repaired on a 10-year base. Furthermore, at the occurrence of Cathodic Protection replacement operations, the 33% of the total CS reinforcement in the concrete cap is replaced (CP1 operations indicated in Figure 3 every approximately 30 years). Additionally, the existing corner sheet piles, which are the most exposed, are removed and replaced with new corner sheet piles. The replacement activity includes strengthening of the existing structure through the installation of two additional adjacent sheet piles that enhance the wall capacity in the corner location.

With regards to the FRP-RC/PC design, the scheduled maintenance operations consist of minor repairs to concrete taking place every 10 years. The patching activities for the FRP-RC/PC alternative are estimated at 33% of the CS-RC/PC design in terms of volume for both sheet piles and bulkhead cap.

This assumption is based on the primary concern of substructure corrosion for the CS-RC/PC design, constantly subject to significant chlorides levels. In fact, as the steel rebars begin to corrode, iron oxides (with a greater volume than the metal ions) form on the rebars surface. This cause an increment in volume of the steel rebars that leads to internal stress within the surrounding concrete, which will crack [21]. As cracks appear, they allow more chlorides to reach the reinforcing steel, thus causing more corrosion and build-up of iron oxides. This means more internal stress within the concrete, more cracks, and so on [21]. The cracks will enlarge, eventually leading to spalling of the concrete and loss of load bearing capacity of the structure. This phenomenon is absent in the FRP-RC/PC alternative, and the patching can be done more sporadically. Thus, the only surface may need to be sporadically patched for performance or aesthetical reasons at a rate of one third of the CS-RC/PC counterpart.

LCC and LCA methods

LCA and LCC analyses are performed in compliance with the international standards ISO 14040:2006 [22], ISO 14044:2006 [23], and ISO 15686-5 [24]. The software adopted for LCA is SIMAPRO (PRè Consultants, 2018, version 8.5.2.0) [25].

GOAL AND SCOPE

In compliance with ISO standards, it is mandatory to define goal and scope of an LCA [22] [23] [24]. In the present work, the LCA of the Halls River Bridge is performed to assess the level of environmental sustainability of a transportation infrastructure built only with non-corrosive FRP reinforcement. To highlight possible benefits associated to the deployment of FRP reinforcement, the environmental performance of the FRP-RC/PC design is compared to a traditional CS-RC/PC alternative. The study is performed at the design stage. The scenario is from cradle-to-grave.

FUNCTIONAL UNIT

For the purpose of the analysis (i.e., to evaluate the environmental performance of an infrastructure reinforced with only FRP), the FRP-RC/PC bridge alternative is chosen as Functional Unit (FU) considering its entire service life of 100 years. An alternative CS-RC/PC design is considered for comparison. For consistency, it is necessary to adopt the same functional unit also for the CS-RC/PC alternative considering a reference period of 100 year. The service life of the CS-RC/PC alternative is limited to 75 years. Thus, it is assumed that after 75 years the bridge is demolished and a new one is re-built with the same technology.

LIFE CYCLE IMPACT ASSESSMENT (LCIA) METHODS

The impact assessment method chosen to perform the LCIA is based on the software [26] Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI, version 2.1) [26] as suggested by ISO 21930:2017 [27]. TRACI is a midpoint oriented LCIA methodology developed by the U.S. Environmental Protection Agency (EPA) specifically for applications within the US. ISO 21930:2017 provides a list of mandatory impact categories to be considered when assessing environmental sustainability of construction products These include: Global Warming Potential (GWP 100), Ozone Depletion Potential (ODP), Eutrophication Potential (EP), Acidification Potential (AP), and Photochemical Oxidant Creation Potential (POCP). In this study, only mandated impact categories are discussed. Characterization factors are those implemented in the last version of the software TRACI.

Although TRACI is substantially a midpoint method, normalization factors for USA and Canada are available [28]; then, in order to highlight the relevance of different impact categories, normalized results will be also included. In this way, comparability between the two bridge options is greatly facilitated.

DATA SOURCE & QUALITY

The primary sources of data for the LCC and LCA analyses are the construction plans and the field data collected on site during bridge construction. The inputs are selected to highlight the differences between the two design options and ease their comparison. Thus, all the structural elements are included. Conversely, secondary items that have minor impact on the results of the analyses are not included for clarity. Secondary items include: Maintenance-of-Traffic (MOT) devices, temporary barrier walls, surveying activities, rip-rap, embankment, drainage systems, asphalt, guardrails, signage devices and utilities.

Bridge elements included in the inventory are reported in Table 2, where amounts and materials are specified. In Table 3, details are given about materials and components sources, means of transports and average distances from supplier to construction site.

Secondary data are relative to materials productions and means of transport; the source is the database Ecoinvent (version 3.4) [29]. The system model adopted in the analysis is the 'allocation, recycled content' or 'cut-off' which allocates primary production of materials to the primary user. If a material is recycled, the primary producer does not receive credit for providing the recyclable material. Therefore, recyclable materials are available burden-free for recycling processes and secondary materials bear only the impacts of the recycling processes.

LCC Analysis

PRODUCT STAGE

GFRP bars and CFRP strands are commercially available in geometries and shapes equivalent to CS counterparts. They are manufactured through pultrusion of resin-impregnated bundles of fibers. The resin can either be vinyl ester or epoxy. Glass fibers are typically of the corrosion-resistant (E-CR) type. Carbon fibers are typically of the high-modulus type. The price of FRP bars and strands is typically higher with respect to CS reinforcement, as shown in Table 4. The price gap is expected to narrow as the technology achieves wider acceptance and the market enlarges [30]. For CS bars a unitary price of 1.32 $/kg is considered, for the CS strands a price of 3.30 $/m is considered. Whereas, FRP pricing by weight is not customary and bars and strands are priced by unit length. The FRP unitary price varies at varying diameter and is based on manufacturers price schedules and private FDOT indexes. The amount of FRP reinforcement required to reinforce an equivalent RC or PC element is typically higher with respect to CS, as shown in Table 1. The use of FRP reinforcement is justified by its superior durability that is expected to reduce maintenance costs.

As detailed discussing the two design alternatives, the use of FRP reinforcement allows to deploy recycled materials such as RCA and RAP in the concrete mix, along with seawater in some elements of the structure. The variation in the concrete mixes has limited influence on the unit cost of concrete but may have a more significant impact from the environmental perspective. Details are discussed at the LCA level. Corrosion mitigation methods for the CS-RC/PC alternative include using silica fume in the concrete mix. Due to such requirements, the cost of PC elements (bearing piles and sheet piles) is increased by 19.69 $/m and the cost of CIP elements of the substructure (bulkhead caps and bent caps) elements is increased by 52.32 $\$/m^3$, as per FDOT historical cost information (FDOT, 2018).

The costs related to the accessories for working activities have been neglected. Variability and uncertainty in tools and materials makes their assessment complex. Moreover, they do not change from one design to the other, so they do not have impact on the comparative assessment.

CONSTRUCTION STAGE

The weight of GFRP bars is approximately ¼ of the weight of CS counterparts. The implications of the reduced weight of FRP on the transportation costs of the bare reinforcement may be significant [12]. The use of GFRP-RC cast-in-place elements may reduce transportation costs of reinforcement to a ratio approximately 0.25 to 0.5 with respect to steel. Additionally, FRP light weight allows for easier on-site handling and improved productivity implications that can reduce labor crews of about 20% [3]. However, given the need of more reinforcement for the FRP-RC/PC alternative (Table 1), this study accounts for same number of reinforcement placers for both alternatives.

Additional details concerning the construction costs for sheet piles, piles, bulkhead caps, girders and deck are presented by [3].

While savings are expected on the transportation and construction side, the use of FRP reinforcement introduces additional testing costs not experienced with CS reinforcement [30] [31]. For this case study, the Florida Department of Transportation (FDOT) requires each lot of FRP reinforcement to undergo specific testing before acceptance [32]. Required tests must be performed by an approved independent laboratory. For the case considered, the testing cost adds up to $16,060, assuming a single lot of GFRP bars is used for the construction of all the CIP elements.

Table 5 summarizes the costs at the product and construction stage for each element of the FRP-RC/PC alternative. Table 6 summarizes the costs at the product and construction stage for each element of the CS-RC/PC alternative. For precast elements the total cost at the product stage includes the fabrication of reinforcement and concrete, and casting of precast elements. The transportation cost is decoupled and shown in a separate column. For CIP elements the total cost at the product stage includes the bare costs of reinforcement and concrete, and the transportation to the job site. For CIP elements, data available did not allow to decouple the transportation costs that are included in the total costs at the product stage.

Based on the above, the construction cost of the FRP-RC/PC bridge is $6,015,645, while the construction cost of the CS-RC/PC bridge is $5,514,278.

USE STAGE

Table 7 shows the costs associated to the pile maintenance and repair operations. Table 8 shows the costs associated to the sheet piles and bulkhead cap maintenance and repair operations. Each table is divided into two sections: one for each alternative design. Cost estimations are based on existing FDOT inventories and historical repair cost database [33].

END OF LIFE STAGE

The end-of-life cost includes the demolition of the structure, its re-construction, and disposal of the debris to landfill. Demolition and re-construction activities are costs, while the recycling of reinforcement scrap is a recovery (profit). Steel is considered as a fully recyclable metal, with the 90% of its weight assumed to be resold and the remainder to be landfilled.

Demolition and reconstruction cost

The demolition cost for both the FRP-RC/PC and CS-RC/PC alternatives is estimated at $573,352. The estimation is based on FDOT database and inventories [33]. The assumption neglects the fact that demolition of FRP-RC/PC may require reduced machinery given the fact that FRP bars and strands can be easily cut through [3].

GFRP bars may experience strength degradation in alkali exposure [34], and CFRP strands may experience creep rupture and excessive relaxation over the long period [35]. For these reasons, even if FRP is not affected by corrosion, an FRP-RC/PC structure may reach a condition of structural deficiency. Thus, FRP-RC/PC structures may need to be demolished at the end of their service life.

Recycling

The price of scrap metal fluctuates and is influenced by several factors. It is particularly affected by the price of virgin metals, cost of energy and production, and supply and demand. The price for recycling prepared scrap carbon steel is estimated at 0.18 $/kg. The steel reinforcement price based on weight is presented in table 9.

Similarly, concrete may be recycled into roadbeds or RCA. Table 10 summarizes concrete recycling price based on weight. For both steel and concrete, the total price accounts for a 10% rate of material that is wasted during the process because of geometry constraints, transportation process or unexpected occurrences.

Research is still underway to address the challenge of FRP recycling [36] [37]. A feasible solution is the reuse of FRP as aggregate for concrete pavements or abutments [38]. Since there is no current cost data available, the present research does not include any pricing of scrap recycling for FRP solution. Only concrete recycling is accounted for as done for the CS-RC/PC alternative in Table 10.

SECOND LIFE

The 100-year reference period selected for this study requires the CS-RC/PC alternative to undergo one demolition and a reconstruction. The reconstruction cost of the CS-RC/PC bridge is assumed to be equal to the cost of the construction of the first structure and is estimated $2,614,482 at year 75 (discount rate included and assumed at 1% as per [39]). For the purposes of this study, only one third of the second life of the structure is used. Assuming that the reconstruction cost is uniformly absorbed over the 75 years of second life, an equivalent cost equal to one third of the total amount can be considered in the calculations ($871,485).

USER COSTS

User costs are computed separately with respect to the direct costs experienced by the owner. They account for traffic delay and service disruption experienced by users during construction and maintenance operation. The two-lane traffic during construction is limited to one travel lane, phased by traffic lights and assisted by trained flaggers. The deployment of FRP reinforcement is expected to speed up single construction operations but not to have a significant impact on the overall construction schedule. Thus, the same user cost during construction is expected for both the FRP-RC/PC and the CS-RC/PC alternatives. The user cost during construction is estimated at $72,545 by [12].

Concerning maintenance operations, the FRP-RC/PC alternative does not require major intervention that cause traffic disruption. Thus, the user cost related to maintenance and repair operation for the case of FRP-RC/PC adds up to zero. Conversely, cathodic protection and sheet pile replacement activity requires to limit traffic access to the bridge to a single lane. Thus, user cost adds up to each maintenance and repair operation for the CS-RC/PC alternative and are estimated at $2,667 per operation.

LCA Analysis

LCA analysis adopts the same framework discussed for LCC. Different assumptions are detailed in the following.

Concrete mixes used in different bridge components are reported in Table 11. All bridge components are cast–in-place (CIP) apart from bearing piles, sheet piles and girders; for details see Table 2. Transports relative to materials for CIP elements are included in the in the transport to construction site (A4) together with only bearing piles, sheet piles and girders. Details about means of transport and distances are in Table 3.

At the construction stage, detailed working times and machines is considered in the LCA analysis at the construction phase, but not labor is included, as recommended by ISO standards [23].

At the use stage, only materials for maintenance and repair are included. No hypothesis on labor and machinery used has been done; indeed, the level of uncertainty introduced could be very high. Total amounts of materials used in maintenance and repair are listed in Tables 7 and 8.

At the end of life stage, in line with the default allocation procedure adopted, after demolition of the bridge the C&D waste is transported to a recycling center. No avoided burden is considered for concrete and steel recycling. Advantages coming from steel recycling are considered.

For consistency with the FU selected, it is assumed that the CS-RC/PC undergoes reconstruction at the end of its service life of 75 years to reach the end of the reference period of 100 years. It is assumed the burden of reconstruction to be uniformly absorbed over the second life of the structure and only one third of the second life is exploited for comparison purposes. Thus, the bridge reconstruction is accounted in the analysis for one third of its burden.

Results and Discussion

LCC

Considering only the construction stage, the initial cost of the FRP-RC/PC design is equal to $ 6,015,645. The initial cost of the CS-RC/PC alternative is equal to $ 5,514,279. Thus, the initial cost associated to the CS-RC/PC design is 8% lower with respect to the FRP-RC/PC alternative. Considering the entire reference period for the two structure and including maintenance, repair, demolition, and reconstruction activities, the undiscounted cumulative cost of the FRP-RC design is equal to $ 6,211,677. The undiscounted cumulative cost of the CS-RC/PC alternative is equal to $9,827,580. Thus, the undiscounted cumulative cost associated to the CS-RC/PC design is 58% higher with respect to the FRP-RC/PC alternative.

When analyzing currency fluxes occurring at different times, the value of the currency must be discounted to present value to have a representative comparison. The Net Present Value (NPV) of each expense can be computed and summed up to obtain the cumulative NPV for the two design alternatives. For NPV methods refer to [40]. Considering all the expenses that occurs over the reference period of 100 years and assuming a discount rate equal to 1% the cumulative NPV for the FRP-RC/PC alternative is computed at $ 6,287,592. Similarly, the cumulative NPV for the CS-RC/PC alternative is computed at $ 7,858,262 as shown in Table 12. Thus, the cumulative NPV associated to the CS-RC/PC design is 25% higher with respect to the FRP-RC/PC alternative. The influence of the discount rate on the cumulative NPV is assessed through a sensitivity analysis presented in the next section.

The difference between the two design alternatives can be quantified in absolute term computing the Net Saving (NS) as the difference of the NPVs associated to the two design alternatives. The NS is estimated at $ 1,570,670. The concept of NS can be further developed into Annual Saving (AS). When comparing two alternatives analyzed over the same reference period, the AS can be calculated as the NS divided by the reference period of 100 years. The AS is estimated at $15,707. Figure 5 shows the cumulative NPV for the two design alternatives until the end of the 100-year reference period. To ease the reading of results, the y-axis is offset at $ 5,000,000 rather than zero. The maintenance activities of the CS-RC/PC bridge are marked in Figure 5 in Roman numbers (from I to IX and from XII to XIII). Point X represents the sum of demolition and re-construction activities, while point XI represents the profit given by the steel recycling. At EOL, the FRP-RC/PC includes demolition and re-cycling activities as well.

The breakeven point (i.e. the intersection between the two alternatives) occurs at t = 41 years. The breakeven point defines the payback period for the additional investment required for the construction of the FRP-RC/PC alternative.

LCC SENSITIVITY ANALYSIS

The discount rate (r) reflects the value of money over time and is used to evaluate future costs in relation to present costs, accounting for the prevailing interest and inflation rates [41]. The cumulative NPV is sensible to variations in the value of the discount rate. The higher the discount rate, the lower the impact of future expenses on the cumulative NPV. In the limit case of a very high discount rate, the cumulative NPV would tend to be equal to the initial cost. In this case maintenance, repair, demolition, and reconstruction activities have minimal influence on the cumulative NPV. In the limit case of a discount rate equal to zero, the cumulative NPV would be equal to the cumulative cost. In this case maintenance, repair, demolition, and reconstruction activities would have the same impact of the initial construction cost.

In the analysis, the discount rate is set at 1.0%. The value is higher with respect to the value of 0.6% proposed by the White House Office of Management and Budget (OMB) in circular A-94 (revised November 2017) [37]. Considering a higher discount rate reduces the influence of maintenance, repair, demolition, and reconstruction activities that the CS-RC/PC alternative undergoes through the 100-year reference period. Therefore, the gap between the two alternatives in terms of NS and AS is reduced. This provides a more conservative estimation of the savings resulting from to the deployment of FRP reinforcement. Many scholars including [42] and [43] prescribed a rate close to or equal to zero. The Society of Environmental Toxicology and Chemistry (SETAC) recommends a 0.01 % discount rate for long-term investments [44]. On the other side, in the literature, discount rate values ranging from 3% to 5% are typically used on transportation projects. The present study is based on the value of 1%, as suggested by [39] and in line with the real discount rate value suggested by the recent White House Office of Management and Budget (OMB) circular A-94 (revised November 2017) [45]. As detailed in the circular available to the public, the real rates are to be used for discounting constant-dollar flows, as is often required in cost effectiveness analyses, whereas nominal rates are to be used for discounting nominal flows, which are often encountered in lease-purchase analysis. The authors believe to be on the safe side in adopting a 1% discount rate, when the OMB circular suggests a real discount rate value of 0.6%. However, by inspecting the past OMB circulars, authors indicate that the 10-years real rates average (period 2007-2017) is 2%. Similarly, the nominal rates average of the past 10 years is 3.9%. The discount rate OMB historical database show that there is a general down trend of the discount rate value over time. Given the OMB historical trend and current state, authors believe values between 0.6% and 2% as best options. Authors are aware of the importance of the discount rate value, thus authors investigated a necessary sensitivity analysis.

A sensitivity analysis is performed to investigate the influence of a variation in the discount rate over the cumulative NPV of the two alternatives. Figure 6 shows how the NPV associated to the two design alternatives decreases at increasing discount rate. The effect is negligible no the FRP-RC/PC alternative that experiences minimal maintenance. Conversely, the effect is relevant on the CS-RC/PC alternative that experiences relevant maintenance, repair, and reconstruction costs. The breakeven point occurs at a discount rate of 4.0%. In an economic scenario where the discount rate is higher than 4.0% the deployment of FRP reinforcement is not convenient from an economic perspective. The breakeven point is far from the value of 0.6% that is deemed representative of the current economic situation with a projection of 30+ years [45].

LCA

Tables 13 and 14 show the environmental impacts for the two alternatives. At the construction stage (A1 – A5), the two alternatives have comparable environmental performances (Figure 7a). While both alternatives show similar results in terms of global warming, the FRP-RC/PC alternative has superior impacts in terms of ozone depletion, but it performs better in terms of eutrophication. For the other two categories, i.e. acidification and photochemical oxidant creation, the CS-RC/PC alternative is slightly better than FRP one. Instead, comparing the environmental performances of the two alternatives over the 100-year reference period in four out of five categories the FRP-RC/PC alternative is less impacting with respect to the CS-RC/PC (Figure 7b). The FRP-RC/PC alternative has a higher impact just on ozone depletion with respect to the CS-RC/PC alternative. The difference is relevant in relative terms as shown in Figure 7b, where in each category percentages are computed using the most impacting alternative as a reference. However, the ozone impact of the FRP-RC/PC alternative may be not representative of the current state of the practice; indeed, the parameter is mostly affected by the activities related to the production of CFRP strands and an updated database is not available to the public.

However, to better clarify the relevance of ozone depletion with respect to the other impact categories and make comparability between the two alternatives more intuitive, Figure 8 shows the normalized impact values. Normalized values clearly show the very low relevance of the ozone depletion category with respect to other impacts. Global warming, acidification and photochemical oxidant creation have middle relevance, while eutrophication outweighs all the others. In the cradle-to-grave scenario the FRP alternative outperforms RC, confirming what has been already highlighted by results at the characterization level.

Figure 9 shows the relative contribution of each phase on each impact category in percentage terms. Percentages are computed using the total impact that each design alternative has on each category as a reference. For both the FRP-RC/PC and the CS-RC/PC alternative, the product stage (i.e., A1-A3), has the largest environmental impacts in each category considered (Figure 9).

Conclusions

This paper investigates the financial and environmental implications of two designs alternatives for the Halls River Bridge, a short-spanned vehicular bridge located in Homosassa (FL). An FRP-RC/PC design and a traditional CS-RC/PC design are considered. Based on the design plans, field data collected during construction, maintenance and EOL models defined for both alternatives LCC and LCA analyses are conducted for both alternatives. The two design alternatives are compared, and the following conclusions outlined:

1. The service life is shorter for the CS-RC/PC alternative design, and the structure requires more frequent maintenance and repair activities with respect to the FRP-RC/PC alternative. The service life for bridges is not currently defined in any specification, and it is not related to the design life, or the probabilities associated with it. The service life for the CS-RC/PC alternative design was based on current practices in FDOT and backed by a research in the technical literature that averages the service life reported from most DOTs in bridge projects that adopt CS as reinforcement. The service life for the FRP-RC/PC alternative was based on the current expectation of the industry with the deployment of non-corrosive materials, and on several studies that investigate projections by extrapolating accelerated test results of FRP bars in aggressive environments.
2. The unit material cost of carbon steel reinforcement is lower with respect to GFRP bars and CFRP strands. As a consequence, the cost at the construction stage for the CS-RC/PC alternative is 8% lower with respect to the FRP-RC/PC alternative.
3. The FRP-RC/PC alternative shows economic benefits over the long term. The cumulative NPV for the CS-RC/PC alternative is 25% higher with respect to the FRP-RC/PC design. This corresponds to a NS equal to $1,570,670. The cumulative NPV accounts for all the expenses occurring during construction and is computed assuming a discount rate of 1.0%. The NS is the difference between the NPV related to the two design alternatives.
4. The annual saving associated to the FRP-RC/PC design with respect to the CS-RC/PC alternative is computed at $ 15,707. The breakeven point between the two designs occurs at year 41, which corresponds to one of the main maintenance activities for the CS-RC/PC alternative. Passed the breakeven point, the FRP-RC/PC design becomes more cost-efficient with respect to the CS-RC/PC alternative.

5. A sensitivity analysis is carried out to investigate the influence of the discount rate on the cumulative NPV values. A discount rate of 1.0% is selected to provide a current realistic ~~and conservative~~ estimation of the savings resulting from to the deployment of FRP reinforcement.
6. The construction, maintenance, repair, and EOL activities for the two design alternatives feature an impact on the ozone depletion factor that is 7 order of magnitudes less with respect to their impact on global warming, and at least 4 order of magnitude less with respect to their impact on other categories. Thus, the impact of construction, maintenance, repair, and EOL activities on ozone depletion is negligible with respect to other categories that are more affected.
7. The environmental impacts of the CS-RC/PC alternative are higher with respect to the FRP-RC/PC design in four out of five impact categories in the cradle-to-grave scenario, namely global warming, photochemical oxidant creation, acidification, eutrophication. The shorter service life of the CS-RC/PC alternative is a relevant factor in determining its lower performance. This is clearly demonstrated by comparing the two alternatives at the cradle-to-gate scenario; indeed, considering all five categories there is a trade-off between the two alternatives.
8. The impact of the FRP-RC/PC design on ozone depletion is roughly four time the impact of the CS-RC/PC alternative. However, the impact is negligible is terms of absolute magnitude. This is evident by comparing normalized impacts, where the relevance of ozone depletion category appears absolutely negligible with respect to other categories.

ACKNOWLEDGMENTS

The support from the Infravation Program under Grant Agreement No. 31109806.005-SEACON, that made possible the presence of the first author to the job site, is gratefully acknowledged. The views and opinions expressed in this paper are those of the authors and do not necessarily reflect those of sponsors or collaborators.

References

[1] Bakis, Charles E., Lawrence C. Bank, VLet Brown, El Cosenza, J. F. Davalos, J. J. Lesko, A. Machida, S. H. Rizkalla, and T. C. Triantafillou. “Fiber-reinforced polymer composites for construction—State-of-the-art review.” Journal of composites for construction 6, no. 2 (2002): 73-87.

[2] Nolan, S., Rossini, M., & Nanni, A. “Seawalls, SEACON and Sustainability in the Sunshine State.” Transportation Research Board 97th Annual Meeting. Washington, DC. (2018).

[3] Cadenazzi, Thomas, Steven Nolan, Gianbattista Mazzocchi, Zachary Stringer, and Antonio Nanni. “Bridge Case Study: What a Contractor Needs to Know on a FRP Reinforcement Project.” ASCE Journal of Composites for Construction. (2019, submitted)

[4] ACI Committee 440. “Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymes (FRP) Bars.” ACI 440.1R-15. Farmington Hills, MI: American Concrete Institute. (2015).

[5] Fib. “FRP reinforcement in RC structures, Bulletin 40, fib” - International Federation for Structural Concrete, Lausanne. (2007).

[6] AASHTO, AASHTO LRFD. “Bridge Design Specifications.” 8th Edition. Washington, DC: American Association of State Highway and Transportation Officials. (2017).

[7] Rossini, M., T. Cadenazzi, S. Nolan, and A. Nanni. “SEACON and resilient FRP-RC/PC Solutions: The Halls River Bridge.” Italian Concrete Days 2018 (ICD 2018). Lecco, IT: Associazione Italiana Calcestruzzo Armato e Precompresso (AICAP) & Collegio dei Tecnici della Industrializzazione Edilizia (CTE). (2018).

[8] Hillman, John R., and SE PE. "Hybrid-composite beam (HCB) design and maintenance manual." The Missouri Department of Transportation (2012).

[9] FDOT. Standard Specifications for Road and Bridge Construction: “DEV400 – Concrete Structures.” Florida Department of Transportation. (2018).

[10] Rossini, M., F. Matta, S. Nolan, W. Potter, and A. Nanni. “AASHTO Design Specifications for GFRP-RC Bridges: 2nd Edition. Italian Concrete Days 2018” (ICD 2018). Lecco, IT: Associazione Italiana Calcestruzzo Armato e Precompresso (AICAP) & Collegio dei Tecnici della Industrializzazione Edilizia (CTE). (2018).

[11] Belarbi, A. “Guide Specification for the Design of Concrete Bridge Beams Prestressed with CFRP Systems.” Washington, DC: National Cooperative Highway Research Program (NCHRP). (2018)

[12] Cadenazzi, T., Rossini, M., Nolan, S., Dotelli, G., Arrigoni, A., & Nanni, A. “Resilience and Economical Sustainability of a FRP Reinforced Concrete Bridge in Florida: LCC Analysis at the Design Stage.” The Sixth International Symposium on Life-Cycle Civil Engineering (IALCCE). Ghent, NE. (2018).

[13] Zhang, Wu-Man, Ying-Zhou Liu, Hai-Zheng Xu, and Heng-Jing Ba. "Chloride diffusion coefficient and service life prediction of concrete subjected to repeated loadings." Magazine of Concrete Research 65, no. 3 (2013): 185-192.

[14] Cui, Zhen. "Lifetime performance prediction of reinforced concrete structures in multi-threat areas." (2016).

[15] Keller, Mona & Schultz-Cornelius, Milan & Pahn, Matthias. Synergistic effects of alkaline environment on the behavior of GFRP bars under sustained load. CDCC 2017 Fifth International Conference on Durability of FRP Composite for Construction and Rehabilitation of Structures, At Sherbrooke, Quebec, Canada. (2017).

[16] Gooranorimi, Omid, and Antonio Nanni. "GFRP reinforcement in concrete after 15 years of service." Journal of composites for construction 21, no. 5 (2017): 04017024.

[17] EN, CEN. "15804: 2012+ A1: 2013." Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products (2013).

[18] Silica Fume Association (2017). Life-365 v.2.2.3 [computer software]. Retrieved from: http://www.life-365.org

[19] Zhang, Wu-Man, Ying-Zhou Liu, Hai-Zheng Xu, and Heng-Jing Ba. "Chloride diffusion coefficient and service life prediction of concrete subjected to repeated loadings." Magazine of Concrete Research 65, no. 3 (2013): 185-192.

[20] FDOT. Integral Pile and Column Jacket. (2016). Retrieved from: http://www.fdot.gov/programmanagement/Implemented/Workbooks/JulWorkbook2016/Files/SP4570000.pdf

[21] PCA, Types and Causes of Concrete Deterioration, Portland Cement Association, Skokie, Illinois, 2002, 16 pages.

[22] International Organization for Standardization, ISO 14040:2006 Environmental management. Life cycle assessment -- Principles and framework, 2006.

[23] International Organization for Standardization, ISO 14044:2006 Environmental management. Life cycle assessment -- Requirements and guidelines, 2006.

[24] International Organization for Standardization. ISO 15686-5:2017 “Buildings and constructed assets — Service life planning — Part 5: Life-cycle costing.” No. 2017. ISO.

[25] PRè Consultants (2018). SimaPro v. 8.5.2.0 [computer software]. Retrieved from: https://simapro.com/

[26] EPA (2012). TRACI v.2.1. [computer software]. Retrieved from: https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci

[27] International Organization for Standardization. ISO 21930:2017 “Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services.” (2017).

[28] Ryberg, Morten, Marisa DM Vieira, Melissa Zgola, Jane Bare, and Ralph K. Rosenbaum. "Updated US and Canadian normalization factors for TRACI 2.1." Clean Technologies and Environmental Policy 16, no. 2 (2014): 329-339.

[29] Ecoinvent (2017). Ecoinvent v.3.4 [computer software]. Retrieved from: https://www.ecoinvent.org/

[30] Ehlen, Mark A. "Life-cycle costs of fiber-reinforced-polymer bridge decks." Journal of Materials in Civil Engineering 11, no. 3 (1999): 224-230.

[31] ACMA. “Guidelines and Recommended Practices for Fiber Reinforced Polymer (FRP) Architectural Products.” American Composite Manufacturers Association, Arlington, VA. (2016).

[32] FDOT. Standard Specifications for Road and Bridge Construction: “DEV932 - Nonmetallic Accessory Materials for Concrete Pavement and Concrete Structures.” Florida Department of Transportation. (2016).

[33] FDOT. Historical Cost. Retrieved from: http://www.fdot.gov/programmanagement/Estimates/HistoricalCostInformation/HistoricalCost.shtm

[34] Raman, R., Faye Guo, Saad Al-Saadi, Xiao-Ling Zhao, and Rhys Jones. "Understanding Fibre-Matrix Degradation of FRP Composites for Advanced Civil Engineering Applications: An Overview." Corrosion and Materials Degradation 1, no. 1 (2018): 27-41.

[35] Spadea, S., Rossini, M., & Nanni, A. “Design Analysis and Experimental Behavior of Precast Double-Tee Girders with CFRP Strands.” PCI Journal, 63(1), 72-84. (2018).

[36] Dehghan, Alireza, Karl Peterson, and Asia Shvarzman. "Recycled glass fiber reinforced polymer additions to Portland cement concrete." Construction and Building Materials 146 (2017): 238-250.

[37] Correia, João R., Nuno M. Almeida, and João R. Figueira. "Recycling of FRP composites: reusing fine GFRP waste in concrete mixtures." Journal of Cleaner Production 19, no. 15 (2011): 1745-1753.

[38] Yazdanbakhsh, Ardavan, and Lawrence C. Bank. "A critical review of research on reuse of mechanically recycled FRP production and end-of-life waste for construction." Polymers 6, no. 6 (2014): 1810-1826.

[39] Sokri A. “Discounting for Civilian and Military Projects”. GAU Journal of Social and Applied Science. Volume 7, Issue 2:11–15 (2015)

[40] Haghani, Reza, and Jincheng Yang. "Application of FRP materials for construction of culvert road bridges: manufacturing and life-cycle cost analysis." Rapport 2016: 3 (2016).

[41] Sarma, Kamal C., and Hojjat Adeli. "Life-cycle cost optimization of steel structures." International Journal for Numerical Methods in Engineering 55, no. 12 (2002): 1451-1462.

[42] Stern, Nicholas. "The economics of climate change." American Economic Review 98, no. 2 (2008): 1-37.

[43] Dasgupta, Partha. "The Stern Review's economics of climate change." National institute economic review 199, no. 1 (2007): 4-7.

[44] Mistry, Mark, Christoph Koffler, and Sophia Wong. "LCA and LCC of the world’s longest pier: a case study on nickel-containing stainless steel bar." The International Journal of Life Cycle Assessment 21, no. 11 (2016): 1637-1644.

[45] Office of Management and Budget Circular A-94 Appendix C: “Discount Rates for Cost-Effectiveness, Lease Purchase, and Related Analyses”. 2017. Washington D.C. Retrieved from: https://www.whitehouse.gov/wp-content/uploads/2017/11/Appendix-C.pdf

TABLE 1 - FRP to steel reinforcement ratios

Components		FRP/steel ratio
Precast	Girders	2.0
Cast in place	Bent caps	2.0
	Bulkhead caps	1.5
	Deck	1.5
	Concrete traffic railing	1.7
	Approach slab	1.3
	Gravity wall	1.0

TABLE 2 – Bridge components

	Components	Quantity	Materials	Description
Precast	Bearing piles	575.77 m	CFRP-PC	Square section 0.46 m x 0.46 m; CFRP strand and spirals from japan (Tokyo); piles assembled and cast in Jacksonville (Fl).
	Sheet piles	1,395.68 m	CFRP-PC / GFRP-RC	Rectangular section 0.30 m x0.76 m; CFRP longitudinal strand from japan (Tokyo); GFRP transversal reinforcement from Canada; sheet piles manufactured in Jacksonville
	Girders	495.00 m	GFRP-RC	Nine girders per each span (total of five spans); GFRP-RC;
Cast in place	Bent caps	139.38 m^3	GFRP-RC	Six bent caps with six piles per bent
	Bulkhead caps	72.66 m^3	GFRP-RC	
	Deck	998.43 m^2	GFRP-RC	concrete: class IV 5500 psi
	Additional FRP-RC components			
	Traffic railings	149.96 m	GFRP-RC	
	Approach slab	322.37 m^2	GFRP-RC	
	Gravity wall	19.51 m	GFRP-RC	Recycled asphalt pavement (9.75 m), and Recyled concrete aggregate (9.75 m)

TABLE 3 - Transport of bridge components and materials

Elements	Supplier	Means of transport	Distance/time
Bearing piles	Gate precast (Jacksonville, Fl)	▪ CFRP strands and spirals from Japan to Port Everglades via sea freight ▪ CFRP strands and spirals from Port Everglades to Jacksonville via Flatbed ▪ MACK GR64F with two double axle trailers (12.2 m) each (6 piles per truck) from Jacksonville to HRB	11,748 km/1 month shipping 547 km/5 hours 241 km/3 hours drive
Sheet piles CFRP-PC / GFRP-RC	Gate precast (Jacksonville, Fl)	▪ CFRP strands from Japan to Port Everglades via sea freight ▪ CFRP strands from Port Everglades to Jacksonville via Flatbed ▪ MACK GR64F with double axle trailer (12.2 m) from Jacksonville to HRB ▪ GFRP bars from Canada via Flatbed	11,748 km/1 month shipping 547 km/5 hours 241 km/3 hours drive 2503 km/24 hour drive
Girders*	Gate precast (Jacksonville, Fl), Owens Cornings (Nebraska)	▪ GFRP bars from Omaha (NE) to Jacksonville (FL) with Flatbed ▪ MACK GR64F with double axle trailer (12.2 m) from Jacksonville (FL) to HRB	2,556 km/24 hours drive 241 km/3 hours drive
Bent caps, bulkhead caps, deck, Traffic railings, Approach slabs	ATP (Italy), Argos (Brooksville)	▪ GFRP bars from Napoli (IT) via sea freight to Port Everglades (FL) ▪ Flatbed with double axle trailer cronkhite 3300 ewa from Port Everglades to HRB	8,208 km/1 month shipping 473 km/5 hours drive
Gravity wall	ATP (Italy)	▪ GFRP from Napoli (IT) via sea freight to Port Everglades (FL) ▪ Flatbed with double axle trailer Cronkhite 3300 EWA from Port Everglades to HRB ▪ RAP from Miami by truck to Brooksville ▪ RCA from Miami by truck to Brooksville ▪ two different trucks in different days	8,208 km/1 month shipping 473 km/5 hours drive 492 km/5 hours drive
Cast in place concrete	Argos (Brooksville)	▪ Concrete for any Cast in place component ▪ CNG-fueled McNeilus mixer built on a Kenworth chassis, max capacity: 7.3 m^3	31 km/45 min. drive

* Replacing HCB for this study

TABLE 4 – Reinforcement cost difference

Reinforcing bars						
Bar size	**Carbon steel**		**GFRP**		**CFRP**	
	Unit weight [kg/m]	**Cost [$/m]**	**Unit weight [kg/m]**	**Cost [$/m]**	**Unit weight [kg/m]**	**Cost [$/m]**
M10	0.561	0.75	0.159	1.71	N/A	N/A
M13	0.996	1.31	0.281	2.36	N/A	N/A
M16	1.556	2.07	0.427	3.80	N/A	N/A
M19	2.240	2.95	0.607	4.99	N/A	N/A
M25	3.982	5.25	1.046	8.56	N/A	N/A
1x7 15.2mm strand	1.210	3.30	N/A	N/A	0.221	12.50

TABLE 5 - FRP-RC/PC costing construction phase

Item	Product stage [A1-A3]	Transport to job site [A4]	Construction [A5]	Total
Sheet piles	$ 998,410	$ 169,200	$ 332,516	$1,500,126
Piles	$ 269,825	$ 31,104	$ 223,700	$ 524,629
Bulkhead caps	$ 26,146	Included at product stage	$ 33,412	$ 59,558
Pier/pier caps	$ 76,664	Included at product stage	$ 167,577	$ 244,241
Girders	$ 214,130	$ 8,775	$ 115,694	$ 338,599
Deck	$ 205,092	Included at product stage	$ 269,223	$ 474,315
Approach slabs	$ 39,035	Included at product stage	$ 59,612	$ 98,647
Traffic railing	$ 34,331	Included at product stage	$ 24,534	$ 58,865
Gravity wall	$ 3,843	Included at product stage	$ 23,877	$ 27,720
			Total RC/PC-FRP structures	**$3,326,700**

TABLE 6 - CS-RC/PC costing construction phase

Item	Product stage [A1-A3]	Transport to job site [A4]	Construction [A5]	Total
Sheet piling	$ 787,626	$ 169,200	$ 332,516	$1,289,342
Piling	$ 200,234	$ 31,104	$ 223,700	$ 455,038
Bulkhead caps	$ 20,735	Included at product stage	$ 33,412	$ 54,147
Pier/pier caps	$ 37,819	Included at product stage	$ 167,577	$ 205,396
Girders	$ 166,622	$ 8,775	$ 115,694	$ 291,091
Deck	$ 105,274	Included at product stage	$ 269,223	$ 374,497
Approach slabs	$ 26,344	Included at product stage	$ 59,612	$ 85,956
Traffic railing	$ 18,170	Included at product stage	$ 24,534	$ 42,704
Gravity wall	$ 3,285	Included at product stage	$ 23,877	$ 27,163
			Total RC/PC-FRP structures	**$2,825,334**

TABLE 7 – Bearing Piles Maintenance Strategies

CS-RC/PC design			
Strategy	**Repair length (m)**	**Unit cost**	**Tot cost**
Concrete Patching	21.95	$ 121.88	$ 2,676
Installation - Cathodic Protection (CP)	21.95	$ 9,840.00	$216,000
Removal - Cathodic Protection (CP)	21.95	$ 1,640.00	$ 36,000
FRP-RC/PC design			
Strategy	**Repair length (m)**	**Unit cost**	**Tot cost**
Concrete Patching	7.32	$ 121.88	$ 892

TABLE 8 – Seawall and Bulkhead Cap Maintenance Strategies

CS-RC/PC design					
Activity	**Quantity**	**[um]**	**Unit cost**		**Tot cost**
Floating Turbidity Barrier	106.68	[m]	24.80	$/m	$ 2,646
Flowable fill	6.12	[m^3]	152.90	$/m^3	$ 935
Restore spalled areas, epoxy	2.27	[m^3]	13,590.87	$/m^3	$ 30,788
Epoxy material for crack injection	30.28	[l]	23.66	$/l	$ 716
Cracks injection & seal	76.2	[m]	134.55	$/m	$ 10,252
Non-shrink grout – structures rehabilitation	2.27	[m^3]	5,826.93	$/m^3	$ 13,200
				TOT.	**$ 58,538**
Additional CSP and reiforcing steel replacement every CP1					
Activity	**Quantity**	**Um**	**Unit cost**		**Tot cost**
Removal corroded bulkhead cap	56.72	[m]	119.32	$/m	$ 6,825
Reinforcing steel M13 replacement activity	2,578.13	[kg]	2.54	$/kg	$ 6,536
Reinforcing steel M19 replacement activity	105.38	[kg]	2.54	$/kg	$ 267
Concrete Class IV	23.98	[m^3]	160.25	$/m^3	$ 3,843
Removal existing corner piles (no. 8 CP in tot.)	60.96	[m]	103.83	$/m	$ 6,330
Installation of new CSP (no. 3 per each corner)	182.88	[m]	656.17	$/m	$120,000
				TOT.	**$202,340**
FRP-RC/PC design					
Activity	**Quantity**	**Um**	**Unit cost**	**Um**	**Tot cost**
Floating Turbidity barrier	36.58	[m]	24.80	$/m	$ 907
Flowable fill	2.02	[m^3]	152.90	$/m^3	$ 309
Restore spalled areas, epoxy	0.75	[m^3]	13,590.87	$/m^3	$ 10,160
Epoxy material for crack injection	9.99	[l]	23.66	$/l	$ 591
Cracks injection & seal	36.58	[m]	134.55	$/m	$ 4,921
Non-shrink grout – structures rehabilitation	0.75	[m^3]	5,826.93	$/m^3	$ 4,356
				TOT.	**$ 20,889**

TABLE 9 – Steel Recycling Price

Steel recycling at EOL	
Price per kg	$ 0.18
Total CIP elements	kg 124,992
Total Sheet Piles	kg 45,586
Total Girders	kg 4,368
Total Bearing Piles	kg 14,606
Total steel (-10% rate waste)	kg 170,597
Price of recycled steel	**$ 30,088**

TABLE 10 – Concrete Recycling Price

Concrete recycling at EOL	
Price per kg	$ 0.06
Total CIP elements	kg 1,487,257
Total Sheet Piles	kg 935,362
Total Girders	kg 334,343
Total Bearing Piles	kg 315,238
Total concrete (-10% rate waste)	kg 2,764,979
Price of recycled concrete	**$ 167,633**

TABLE 11 – Concrete Mixes

Concrete class type	Application	Quantity [m^3]	Location
Class I nonstructural 2500	AASHTO #57 stone	76.46	Shoulder gutter, Ditch pavement, Slope pavement, Concrete sidewalk and Driveways
Class I nonstructural 2500	AASHTO #89 stone	76.46	Shoulder gutter, Ditch pavement, Slope pavement, Concrete sidewalk and Driveways
Flowable fill	Excavatable	52.98	Miscellaneous Backfill
Class I nonstructural 2500	Recycled concrete aggregate	11.16	50% of Gravity wall
Class I nonstructural 2500	Recycled asphalt pavement	11.16	Remaining 50% of Gravity wall
Class IV 5500	Increased slump (7.25 in)	509.04	Cast in place substructures, deck and approach slabs
Class IV 5500	Seawater	72.63	Bulkhead caps
Class IV 5500	60% Slag - Standard slump	33.11	50% of Traffic Railing (North Side)
Class IV 5500	White cement - Conventional	33.11	Remaining 50% of Traffic Railing (South Side)

Table 12 – LCC results

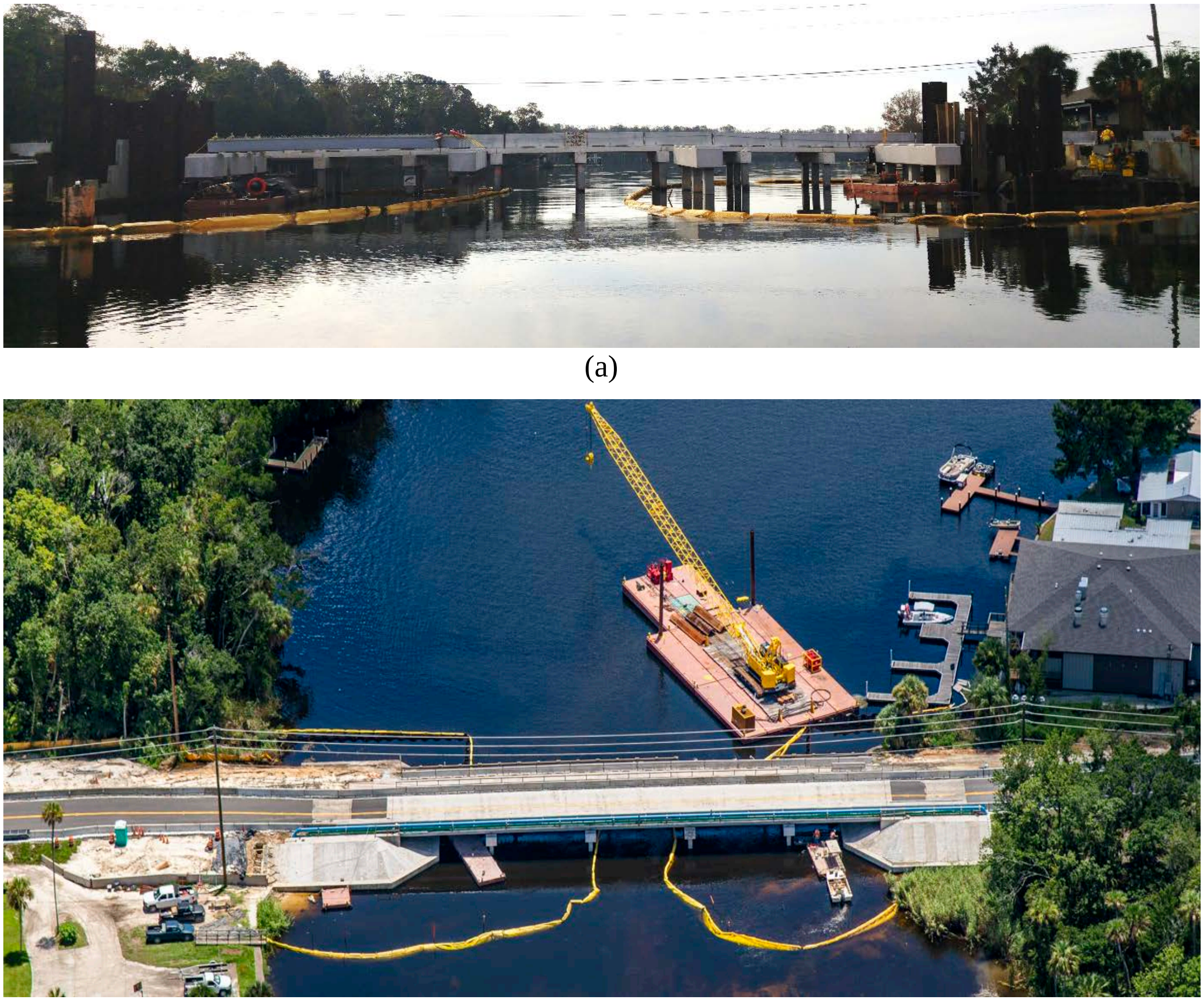
Results				
	CS-RC/PC bridge	FRP-RC/PC bridge	%	User cost
Net Present Value (NPV)	$ 7,858,262	$ 6,287,592		
Net Saving (NS)		**$ 1,570,670**		
Annual Saving (AS)		**$ 15,707**		

TABLE 13 - FRP-RC/PC environnemental impacts

Item	Product stage [A1-A3]	Transport to job site [A4]	Construction [A5]	Use	End-of-life	Total
Ozone depletion [kg CFC-11 eq]	0.486	0.0197	0.0182	0.000359	0.0102	0.534
Global warming [kg CO_2 eq]	883,000	81,200	83,900	8,690	34,300	1,090,000
Photochemical oxidant creation [kg O_3 eq]	51,000	9,430	6,400	422	4,390	71,700
Acidification [kg SO_2 eq]	4,460	421	291	32	185	5,390
Eutrophication [kg N eq]	1,460	92	150	13	42	1,760

TABLE 14 - CS-RC/PC environnemental impacts

Item	Product stage [A1-a3]	Transport to job site [A4]	Construction [A5]	Use	End-of-life	Total
Ozone depletion [kg CFC-11 eq]	0.0619	0.0265	0.0242	0.00175	0.011	0.125
Global warming [kg CO2 eq]	1,180,000	109,000	112,000	35,200	36,700	1,480,000
Photochemical oxidant creation [kg O3 eq]	57,000	11,800	8,530	1,530	4,740	83,500
Acidification [kg SO2 eq]	4,480	495	388	121	199	5,680
Eutrophication [kg N eq]	3,070	120	200	77	45	3,510



(a)

(b)

Figure 1 – HRB substructure (a), and north side after completion (b)

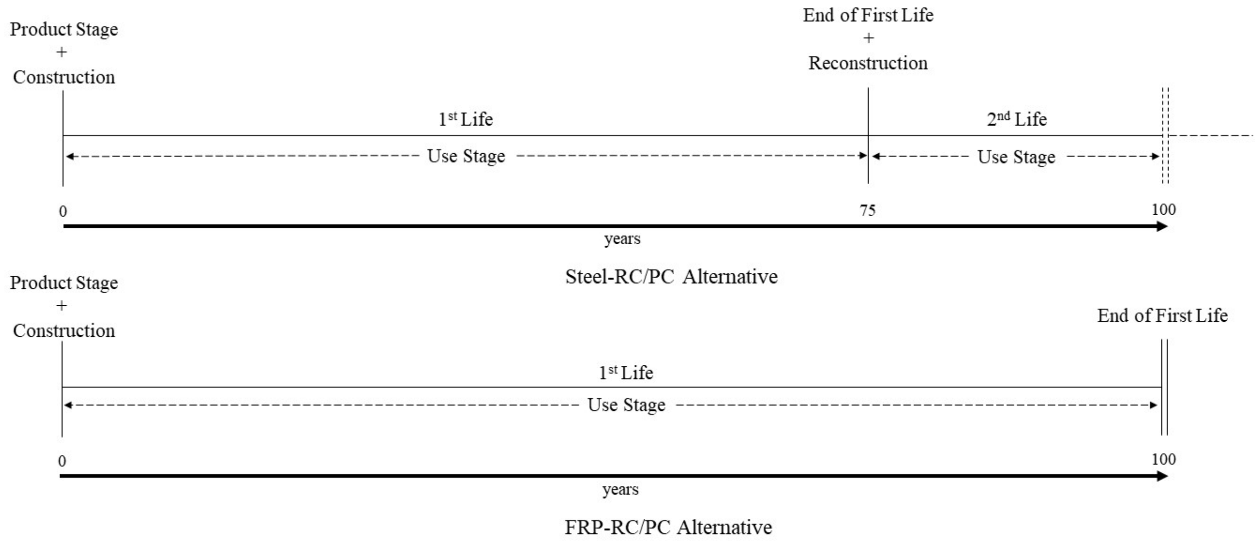


Figure 2 – System boundaries of design alternatives

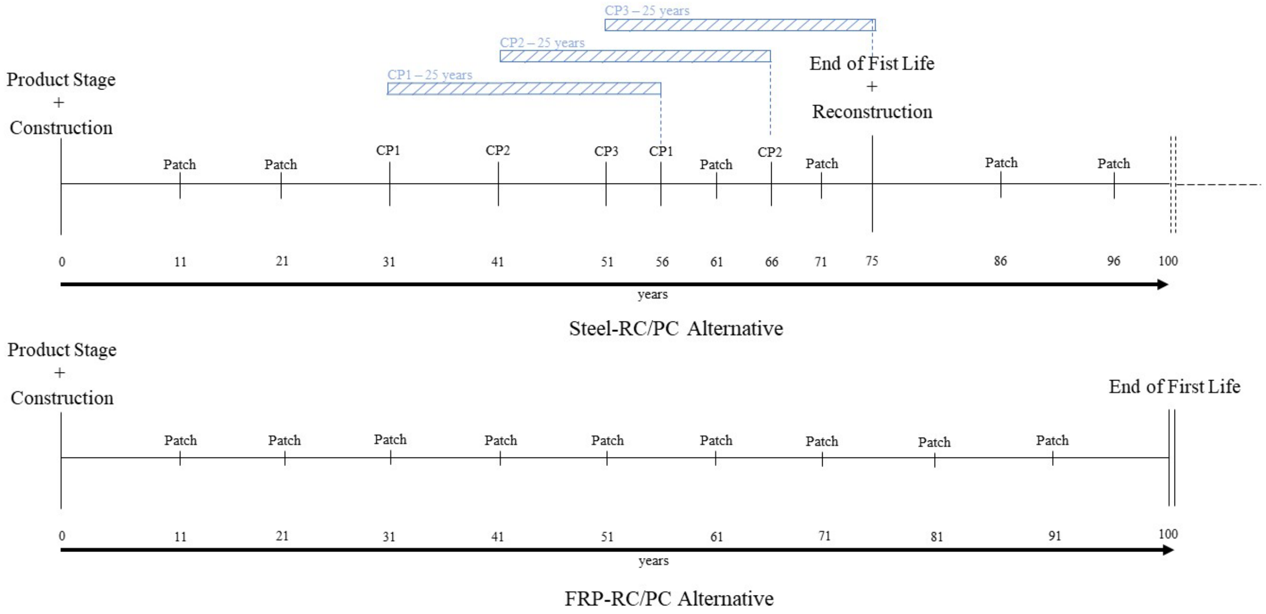


Figure 3 – Life cycle stages of design alternatives

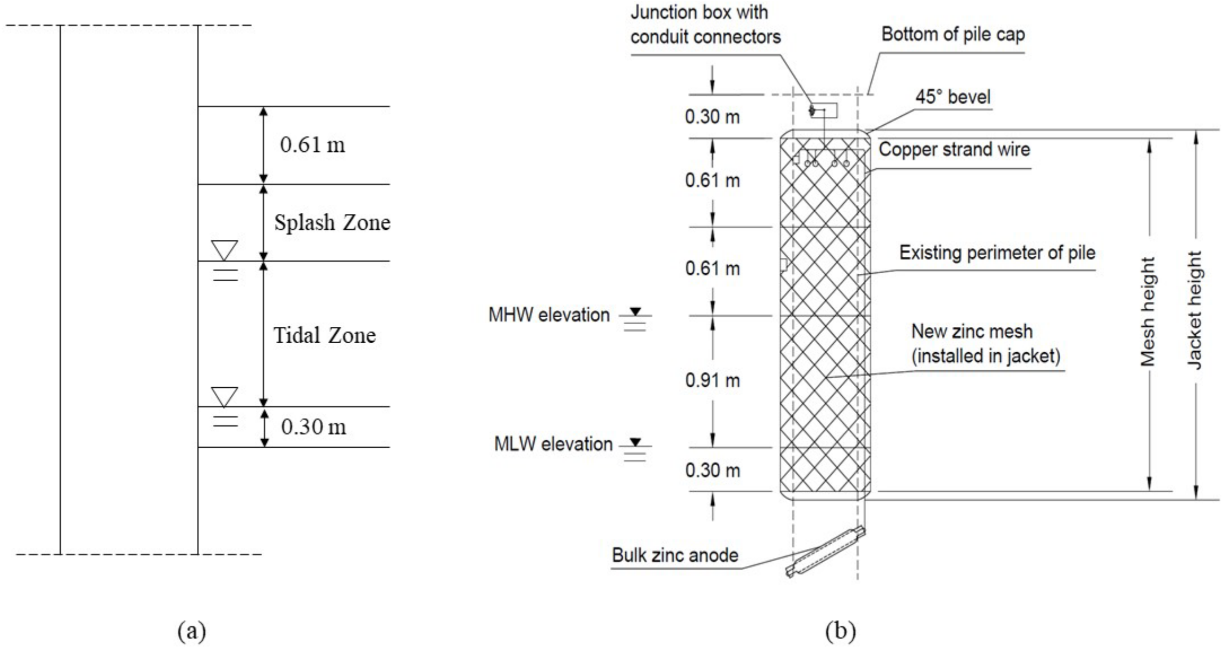


Figure 4 – Zones of corrosion of bearing piles (a), cathodic pile jacket elevation view (b)

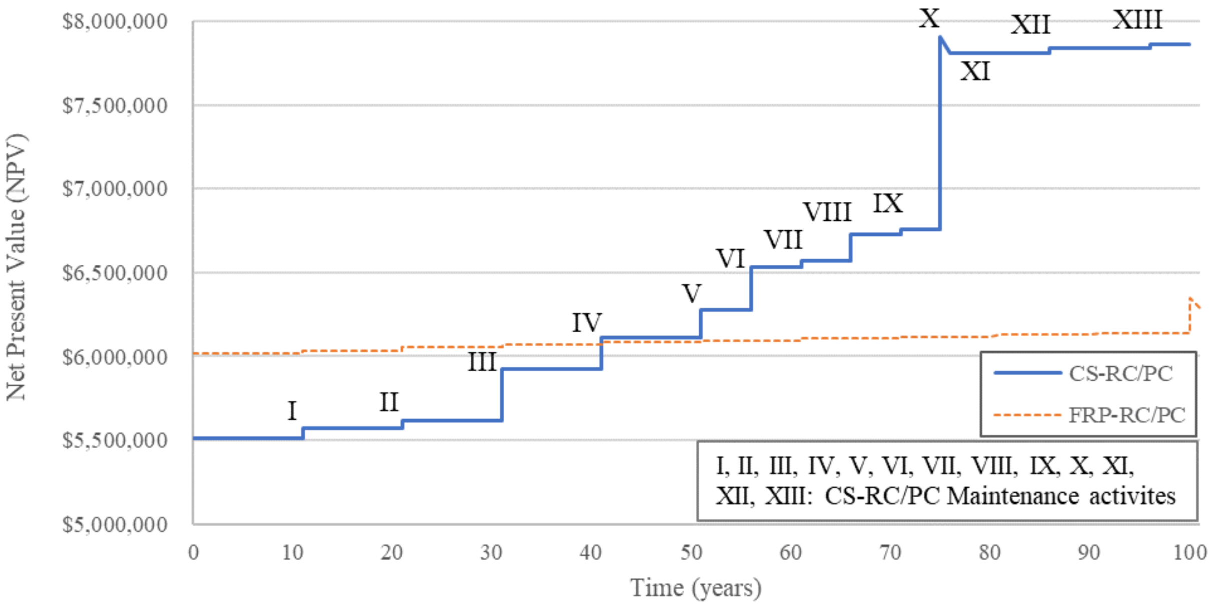


Figure 5 – LCC results considering the baseline scenario where discount rate is 1%

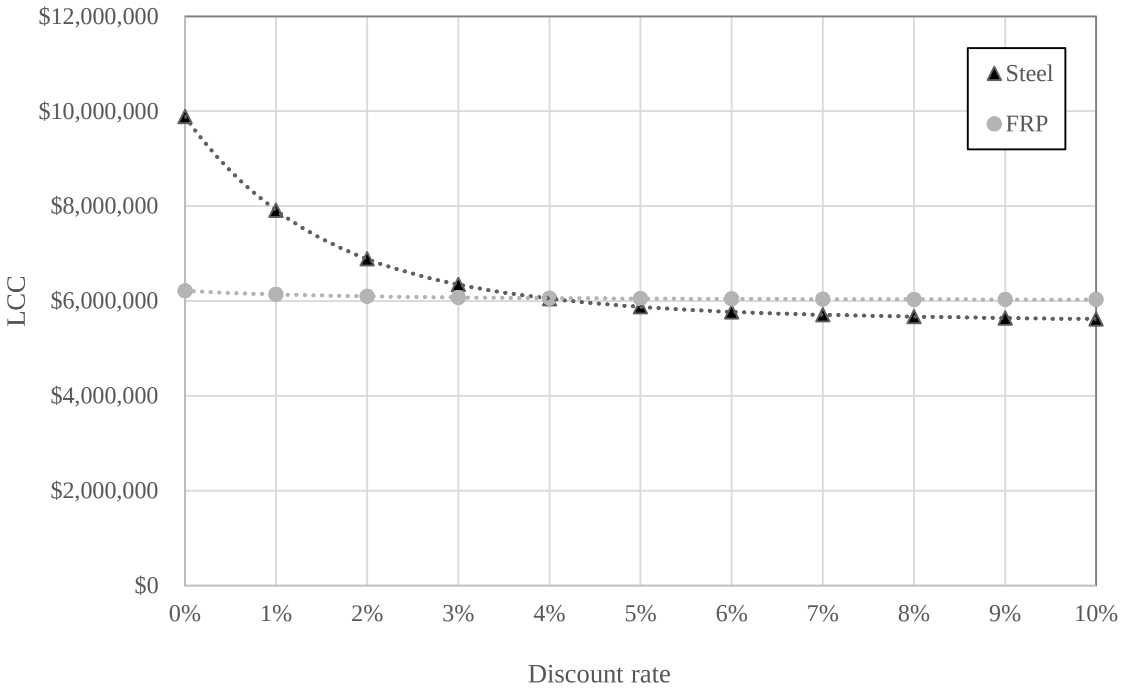
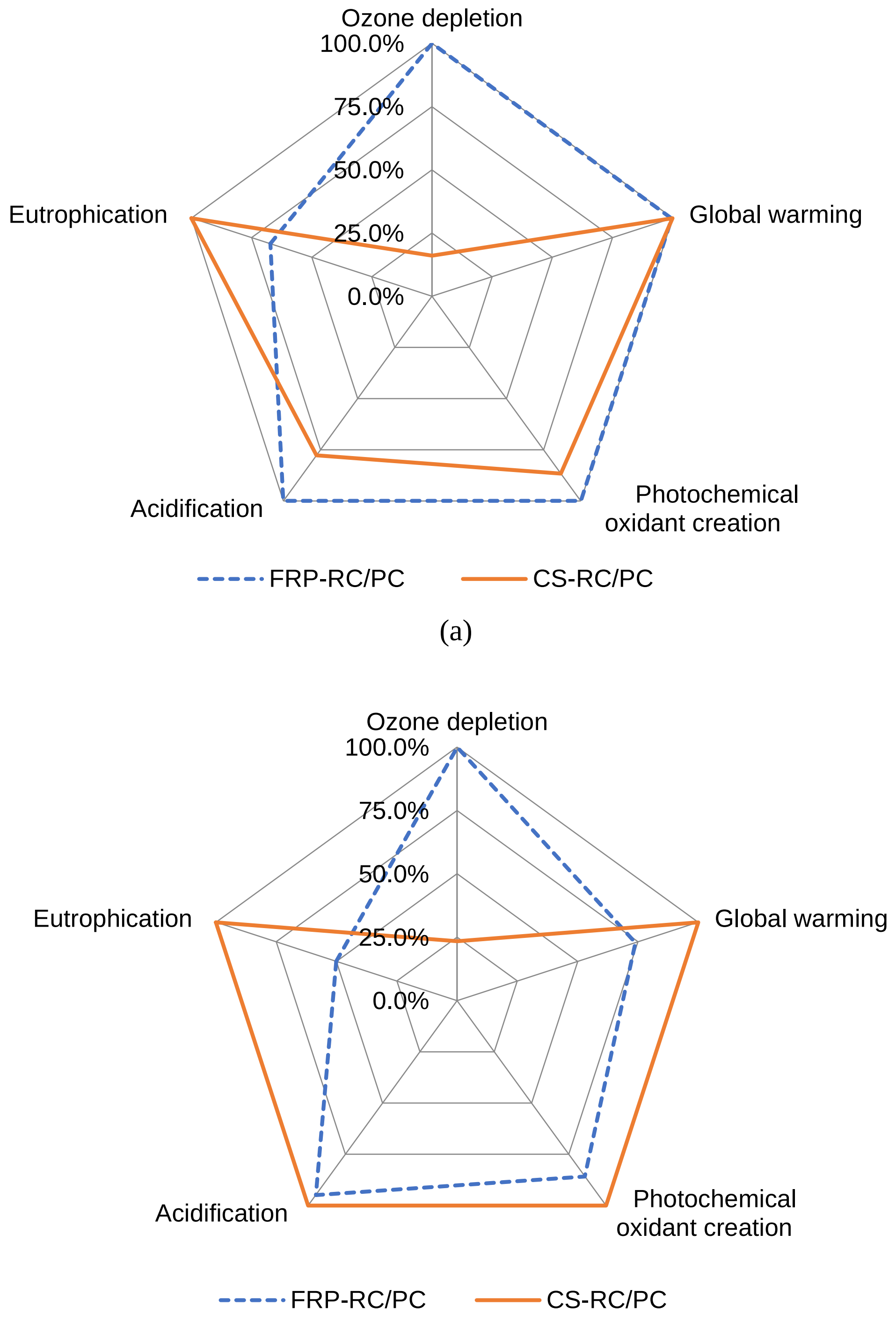


Figure 6 – Sensitivity analysis of LCC results to the discount rate

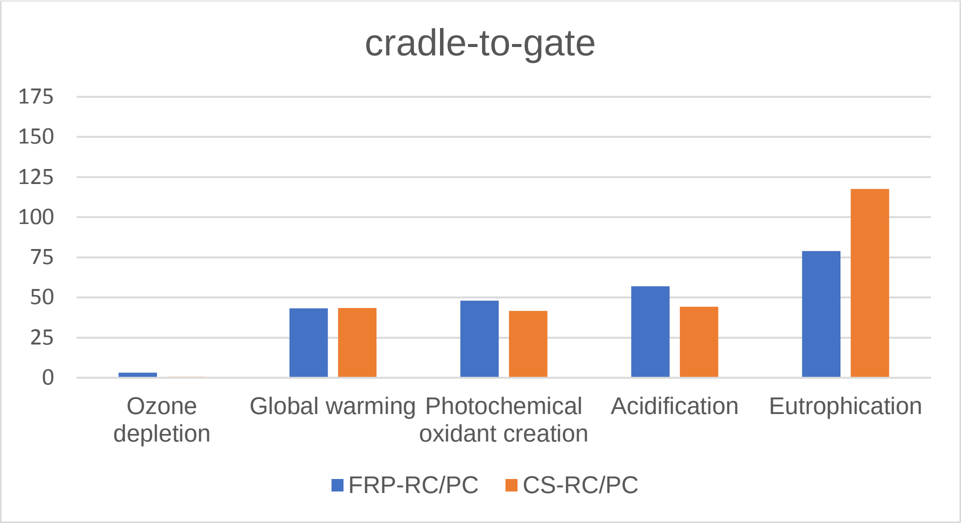


(a)

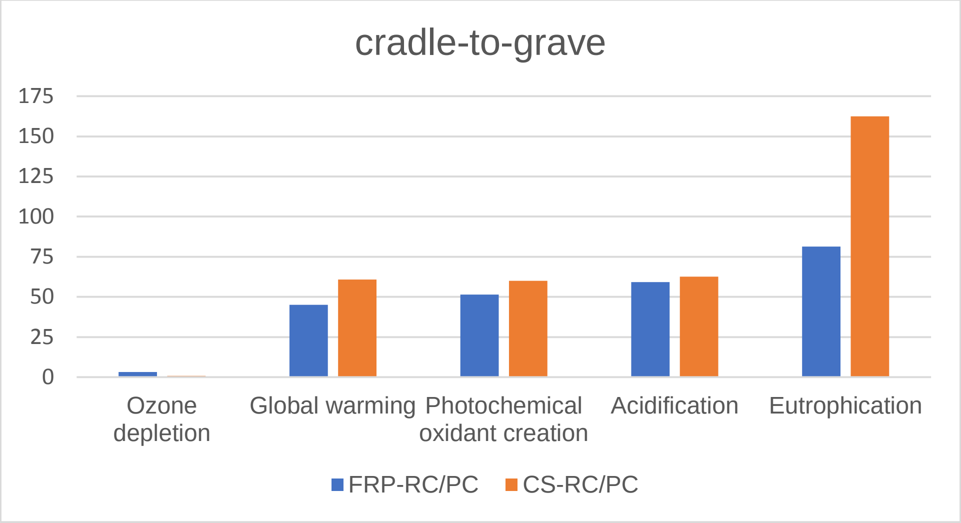
(b)

Figure 7 – Life Cycle Impact Assessment (LCIA): comparison between the two Halls River Bridge (HRB) alternatives, i.e. Fiber Reinforced Polymer-Reinforced Concrete/Pre-Stressed Concrete (FRP-RC/PC) and Carbon Steel-Reinforced Concrete/Pre-Stressed

Concrete (CS-RC/C), at the characterization level: (a) cradle-to-gate scenario; (b) cradle-to-grave scenario; for each category the alternative with the largest impact is set to 100%



(a)



(b)

Figure 8 – Life Cycle Impact Assessment (LCIA): comparison between the two Halls River Bridge (HRB) alternatives, i.e. Fiber Reinforced Polymer-Reinforced Concrete/Pre-Stressed Concrete (FRP-RC/PC) and Carbon Steel-Reinforced Concrete/Pre-Stressed Concrete (CS-RC/C), after normalization: (a) cradle-to-gate scenario; (b) cradle-to-grave scenario

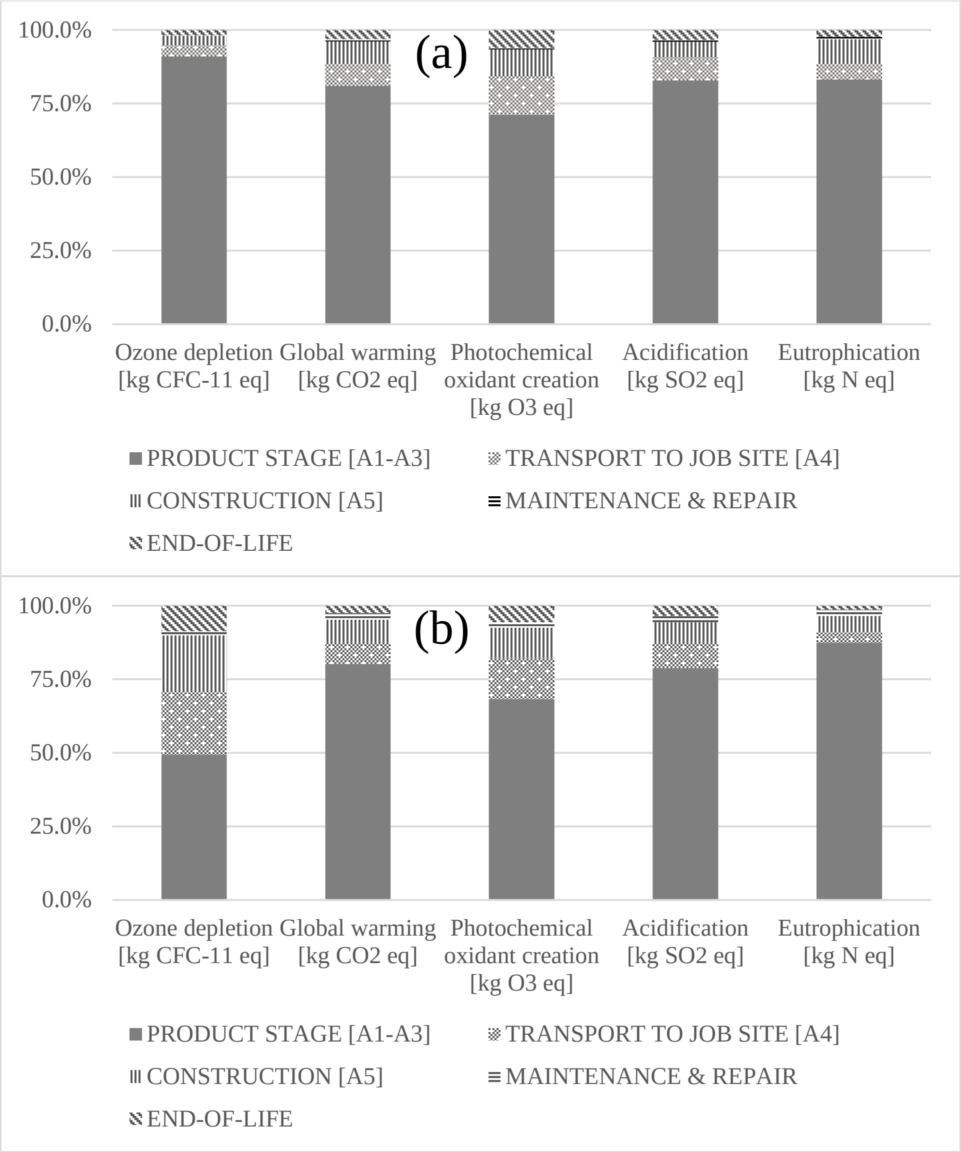


Figure 9 – Life Cycle Environmental Impact Assessment of the two Halls River Bridge (HRB) alternatives: (a) Fiber Reinforced Polymer-Reinforced Concrete/Pre-Stressed Concrete (FRP-RC/PC); (b) Carbon Steel-Reinforced Concrete/Pre-Stressed Concrete (CS-RC/C)