Cost and Environmental Analyses of Reinforcement Alternatives for a Concrete Bridge

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Abstract

Reinforced Concrete (RC) and Prestressed Concrete (PC) structures using conventional materials in aggressive exposure conditions are susceptible to corrosion. Non-corrosive reinforcement materials such as: Glass Fiber-Reinforced Polymer (GFRP) rebars; Carbon Fiber-Reinforced Polymer (CFRP) strands; Stainless-Steel (SS); and Epoxy-coated steel (ECS) reinforcing bars, are attracting attention as more appropriate options in concrete structures. This paper addresses a Life Cycle Cost (LCC) analysis that verifies the cost performance of four different alternative reinforcement bars for the design of a demonstration FRP-RC/PC bridge in Florida, namely Halls River Bridge (HRB). The four different alternatives to be compared are namely Carbon Steel (CS), SS, FRP, and ECS, and the analysis is performed over 100-years. Additionally, a Life-Cycle Assessment (LCA) is included in the analysis to investigate the environmental credentials of the four design alternatives. Cost sensitivity analyses over specific parameters are included. The parameters analyzed are: reinforcement cost, changes in chloride concentration levels over the bridge service life, and discount rate values. Conclusions and recommendations for standard practices and design of future alternative solutions are then presented.

Keywords

Halls River Bridge, FRP-RC/PC bridge, life-cycle cost, epoxy coated steel, stainless-steel, sustainable construction, bridge design, decision-making, LCA.

1. Introduction

The 2017 Infrastructure Report Card by ASCE (ASCE, 2017)) states that about 9.1 % of the bridges in USA were structurally deficient in 2016, with an average age of bridges in USA that is increasing: nation-wide, four bridges out of ten are at least 50 years old, and 15% are 40 to 49 years old. Accordingly, bridge rehabilitation costs have been recently estimated in the order of $123 billion, notwithstanding the recent large investments disposed at all levels of government for repairing bridges. In Florida, only about 15% of the bridges are at least 50 years old, but about 8.5% of all bridges were closed or weight limited, as of January 2015. For this reason, maintenance action is necessary to guarantee serviceability and safety with the annual costs estimated at more than $10 billion (Shepard, 2005). These increasing maintenance costs represent a significant share of bridge ownership costs.

Structural deficiency of bridges, especially in older structures, is mainly due to environmental attack and load effects experienced during their service life. In particular, the main cause of damage in Reinforced Concrete (RC) bridges is corrosion of the carbon steel reinforcement bars, along with cracking and spalling of the cover concrete. This cracking leads to a loss of mechanical performance of the rebars and the surrounding concrete, affecting ultimately the safety of the structure (Sajedi & Huang, 2019). Corrosion effects are generally more serious for substructures in coastal regions due to the ingress of chlorides ions from seawater, or superstructures in cold regions where large amounts of de-icing salts are used, although all parts of the bridge can be affected to varying degrees in either environment. For this reason, RC bridges need regular monitoring, maintenance, repair, and rehabilitation. To this end, life-cycle engineering provides a valuable tool to plan the bridge construction, operation, and maintenance, considering three main pillars: structural safety; costs; and environmental impacts (Xie, Wu, &

Wang, 2018). Moreover, it is possible to adopt cost-effective corrosion management strategies adopting a life cycle perspective (Kere & Huang, 2019). However, few studies have focused on Life Cycle Costing (LCC) of corrosion resistant civil infrastructure applications. Sajedi and Huang (2005) enumerate some of the most relevant studies, and identified a lack of LCC and LCA studies on the use of Fiber-Reinforced Polymer (FRP) rebars in RC infrastructures. The present paper aims to fill this gap.

2. Research significance

The Halls River Bridge (HRB), as shown in Figure 1 during construction activities, provides a real-world test of RC and Prestressed Concrete (PC) using FRP materials as structural reinforcement. The HRB served as demonstrator for the SEACON-Infravation research project (Rossini et al., 2018) and the Florida Department of Transportation (FDOT) Innovation Challenge (FDOT, 2015). Previous studies (Cadenazzi et. al, 2019a; Cadenazzi et al. 2018) analyzed the cost benefits of FRP materials for a full bridge design, using HRB as case study. However, not all the corrosion-resistant alternatives have been fully investigated. To this end, this paper aims to explore the economic viability of using alternative reinforcing.

A recent Virginia Transportation Research Council report (Sharp et al., 2019) discussed and analyzed the approach to LCC studies, when comparing innovative technologies. However, a lack of a robust and balanced approach toward innovation is missing. There is often an inflationary reaction among some contractors towards innovation due to the perception of increased risk. This reaction eventually leads to incorrect pricing of FRP materials and misleading LCC studies. This paper aims to show the relevance of deterministic and accurate LCC studies for the comparison of innovative solutions with long-term benefits, and the implications of risk aversion by contractors.

3. Design and materials

The following four reinforcing materials for RC structures are compared: Carbon Steel (CS); Epoxy-coated steel (ECS); Stainless Steel (SS); and Fiber Reinforced Polymers (FRP). The last three materials are studied and compared with consideration of their corrosion-resistance benefits. Carbon-steel bars are available as Grade 40, 60, or 80 and specifications are issued by ASTM A615/A615M (ASTM 2016). The most commonly specified steel bars are Grade 60, with a yield strength of 414 MPa, an ultimate strength of 621 MPa, and an elastic modulus of 200 GPa. This grade of CS reinforcement is assumed as the benchmark case, for the purposes of comparison. Low-relaxation high-strength carbon-steel bars are available as Grade 250 or 270 and specifications are issued by ASTM A416/A416M (ASTM 2018). Grade 270 is used as benchmark in this study with a yield strength of 1676 MPa, an ultimate strength of 1860 MPa, and an elastic modulus of approximately 195 GPa.

RC structures may experience reinforcement corrosion over time that leads to expansion and spalling of the surrounding concrete (Capozucca, 1995). Corrosion of the bars is a deterioration phenomenon which can ultimately lead to failure under external loads. Spalling accelerates the corrosion of adjacent bars and exacerbates long-term maintenance issues. To delay corrosion, a thin barrier layer of epoxy coating can be applied to protect the bar surface; however, especially in Florida, corrosion still remains a significant problem with the use of ECS reinforced concrete, particularly when a longer service life is required (Sagues et al., 1994). The epoxy coating is an effective corrosion inhibitor, but only as long as the coating remains intact. Imperfections and damage to the bar surface during shipping, handling or installation compromise the protective layer and, thus, the bars ability to resist corrosion over time.

ECS bars and strands shall meet all requirements as of ASTM A775/A775M (ASTM, 2017) and have similar mechanical properties as CS bars. ASTM A775/A775M defines ECS as reinforcing bars with protective epoxy coating applied by the electrostatic spray method, for providing additional corrosion-resistance. The coating thickness measurements shall be 175 to 300 μm for bars sizes Nos. 10 to 16, and 175 to 400 μm for bar sizes Nos. 19 to 57 (ASTM, 2017). ECS strands shall meet the requirements of ASTM A882/A882M (ASTM 2004).

Austenitic SS-316 and duplex 2205 has been selected as the common grades for the SS-RC and SS-PC respectively, specifications are provided by ASTM A276/A276M (ASTM 2017) and FDOT (2018a) given the wide range of studies available to date to prove its performance in RC structures (Freire et al., 2010; Abreu et al., 2006; Veleva et al., 2005) and (Moser, 2012) for PC members. The term austenitic refers to the microstructure of the SS, as detailed in (Gedge, 2008). Thus, SS-316 is often considered one of the most suitable choices when selecting an austenitic SS for marine applications. Duplex 2205 is a more recently developed alternative for prestressing strands. Recent studies by Redaelli at al. 2019, show that preliminary results from service life estimations on austenitic SS-304 bars embedded in seawater concrete, assuming a probability of failure of 10%, guarantee service lives higher than 140 years. Since (Redaelli at al., 2019) refers to a lower SS alloying content (nickel and molybdenum), it is conservative to assume for the purpose of this paper, that the grade SS-316 and 2205 guarantees a service life of 100 years.

FRP represent a proven non-corrosive alternative to CS in new constructions (Spadea et al., 2018). Commercially available solutions include Glass FRP (GFRP) bars for RC and Carbon FRP (CFRP) strands for PC. Deployment of FRP reinforced concrete (FRP-RC) and FRP prestressed concrete (FRP-PC) eliminates the issue of reinforcement corrosion, irrespectively of the concrete mix-design (Bertola et al., 2017). FRP is a brittle composite material, elastic until failure, stronger, but less stiff with respect to CS. The minimum specified values for strength and stiffness of GFRP bars are defined by ASTM D7957 (ASTM, 2017). CFRP strands are not regulated at the federal level, but the FDOT Construction Specifications (FDOT, 2018) include minimum specified values for strength and references to applicable acceptance criteria. Design with FRP is regulated by AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete (AASHTO 2018b) and AASHTO Guide Specifications for the Design of Concrete Bridge Beams Prestressed with Carbon Fiber-Reinforced Polymer (CFRP) Systems (AASTHO 2018a). The amount of reinforcement required is typically in the order of 1.5 times with respect to steel reinforcement in RC applications whereas for PC applications a ratio of 1 is possible. Design of GFRP-RC is typically governed by service considerations including crack-width and deflections limits in reason of its relatively low elastic modulus of approximately 45 GPa.

When using non-corrosive reinforcement like SS and FRP it is possible to reduce the clear concrete cover to 50 mm, as opposed to the 76 mm or 100 mm, typically used in marine substructures from FDOT (FDOT, 2019). Additionally, concrete additives (silica fume, metakaolin, ultrafine fly ash, or for non-submerged applications: corrosion inhibitors) required by FDOT for all CS-RC/PC alternatives in marine environment, do not apply when using SS and FRP (FDOT, 2018a & 2019).

4. Bridge Structure

The 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. Details about the structure of the bridge are discussed by Rossini et al. (2018) and Cadenazzi et al. (2019b) and summarized herein. The structure has five spans for a total length of 56.7 m and a width of 17.6 m. The water way is tidally affected by seawater contamination, particularly during storms.

The structure as-built 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. 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. White cement concrete and another mixture of high-content slag and fly ash are used in the GFRP-RC traffic railings.

5. Life Cycle Model

5.1. LCC – State-of-the-art

Traditional LCC frameworks are generally developed as deterministic analyses, whereby designers assign to each input parameter (such as the cost and frequency of maintenance activities) a fixed value. In a probabilistic analysis, the input parameters are stochastic variables based on assumed or documented mean and standard deviation values, and distribution function. Typically, probability distribution functions for the variables considered in the analysis are performed through Monte Carlo simulations (Hatami & Morcous, 2015). The random sampling model generally includes thousands of iterations that ultimately generates a probability distribution of the maintenance costs.

By comparing a deterministic and probabilistic approach, it is possible to better quantify the effects given by the distributions of sensitive parameters that are dependent on uncertain variables. Additionally, for durability-enhancing materials in general, life-cycle optimization frameworks have been recently developed (Yang et al. 2019), in order to maximize the life-cycle performance and minimize the maintenance cost.

The model deployed in this LCC analysis may be considered state-of-the-practice, rather than state-of-art innovation. However, it is the scope of this paper to present a traditional deterministic framework that can serve as a comparative tool for cost and environmental credentials among four different bridge design alternatives. The parameters of uncertainty are taken into account in the deterministic framework through sensitivity analyses.

5.2. Service life and model boundaries

The main regulations for life cycle analysis are EN 15804 (EN, CEN, 2013), and ASTM E917/E2453 (ASTM, 2013). The model presented in this paper adopts the same nomenclature and procedures presented in the above standards. As widely discussed by Cadenazzi et al. (2019a), the concept of service life is distinct from the concept of design life. There is a number of studies that identify the 75-year period as service life of bridge projects that use CS as reinforcement (Cadenazzi et al., 2019a), whereas with the adoption of innovative enduring materials, the industry aim to assure an extended service life. The life cycle of the FRP-RC/PC and SS-RC/PC solutions comprise the following:

- Material fabrication (or product stage)
- Construction stage
- Use stage
- End of Life (EoL)

The life cycle of the CS-RC/PC and ECS-RC/PC alternatives is composed by:

- Material fabrication (or product stage)
- Construction stage
- Use stage
- End of Life (EoL)
- Reconstruction (which includes new material fabrication and new construction stage)
- Use stage for the 25 years of second life.

The latter includes the fact that only 25 years of the second life are included in the analysis, in order to have the CS-RC/PC and ECS-RC/PC alternatives reach 100-years for a consistent comparison of the four different design alternatives. Additionally, the reconstruction activities (and associated costs and environmental burdens) are accounted for by including one third of the initial construction, assuming that the bridge uses the same design criteria, service life expectation, and construction methods of the original bridge.

5.3. Maintenance model

Life-365 software (Silica Fume Association, 2017) was used to estimate the maintenance schedule for the design alternatives. A chloride concentration value of 14 kg/m^3 was assumed, and the predicted service life of each alternative was the sum of the corrosion initiation and corrosion propagation periods, after which it was assumed the structure encounters a certain level of damage requiring repair (Ehlen et al. 2009). With regards to the CS-RC/PC and the FRP-RC/PC design solutions, the model considers the same assumptions used in Cadenazzi et al., 2019a. This includes the installation and maintenance of cathodic protections (CP) for bearing piles, and either crack repair, CS-reinforcement rehabilitation, or precast element replacement for the CS-RC/PC solution (Cadenazzi et al., 2019a).

With regards to the CS-RC/PC design solution, the level of chloride penetration that triggers corrosion initiation of CS reinforcement is reached at year 12. This value is the corrosion initiation time and for the specific case study is equal to 12 years, time when the chloride threshold of 1.17 kg/m^3 is reached at a concrete depth of 76.2 mm (Figure 2a). The chloride concentration threshold for CS rebars and strands is influenced by a number of variables, and the value selected in this study is consistent with the results presented in a number of publications (Bentz E., & Thomas, M.D.A., 2018; Lindquist et al., 2006; Tanaka et al., 2006; Jin et al., 2010; JSCE, 2007). The level of damage that requires the structure repair is found by summing the corrosion initiation and the corrosion propagation periods (Bentz E., & Thomas, M.D.A., 2018). The corrosion propagation time is equal to 6 years, according to the software Life-365 (Bentz E., & Thomas, M.D.A., 2018). By applying preventive maintenance on concrete at year 12 (corrosion initiation period) the model assumes that the corrosion propagation period is interrupted.

The preventive maintenance is effectively conducted on the bridge “hot” areas prone to corrosion (Cadenazzi et al., 2019a) so that the corrosion initiation period could restart. However, at year 31, the model assumes that the corrosion propagation period, even though partially interrupted, reached in specific areas its limit and the level of damage that requires the structure essential repair is reached. Figure 2b shows the accumulation of chlorides at the rebar surface (embedded in concrete at a depth of 76.22 mm) over time. Figure 2a and Figure 2b refer to both the CS-RC/PC and ECS-RC/PC deterioration model, based on Fick’s second law of diffusion. This model assumes that the initial concentration remains constant over the service life of the bridge.

With regards to the ECS-RC/PC alternative, Life-365 suggests that its service life should be that of CS-RC/PC translated by a number of years that is arbitrarily selected. However, being the same grade of CS, it should undergo the same design criteria as CS with a few minor modifications in development length. For this reason, the ECS-RC/PC is an alternative with the same service life

(75-years) as that of CS-RC/PC, but with an extended routine maintenance interval. In particular, by verifying the steps of the Software Life-365, the maintenance model was found to be translated by 14 years (Bentz E., & Thomas, M.D.A., 2018). In fact, whereas the corrosion initiation time of ECS remains the same of CS, but the corrosion propagation period is increased to 20 years (Bentz E., & Thomas, M.D.A., 2018). For this reason, the cathodic protections (CP) of the ECS-RC/PC design alternative are adjusted accordingly, and the patching activities at year 11, and at year 86 (after reconstruction) have been assumed to be minimal activities, similar to those of the SS- and FRP-RC/PC alternatives. However, from year 21 and year 96 onward, the patching activities undergo the same assumptions of the CS-RC/PC alternative.

Maintenance planning strategies include preventive and essential interventions aimed to extend the useful service life of each bridge design alternative (Biondini & Frangopol, 2016). Figure 3a and Figure 3b represent the maintenance strategies selected to minimize the total expected life-cycle cost. Figure 3a refers to the maintenance strategies selected for the CS-RC/PC and ECS-RC/PC design solution, whereas Figure 3b refers to maintenance strategies selected for the SS-RC/PC and FRP-RC/PC alternative designs.

The FRP-PC/RC maintenance model includes only minimal patching activities on the concrete that conservatively take place every 10 years. FRP materials and concrete, though immune from electrochemical corrosion, do suffer from slow deterioration due to moisture ingress, acid, alkali or sulfate attack, or increased temperatures (Ceroni et al., 2006). Many accelerated lab results and several field studies indicate an estimated 10% to 30% reduction compared to the initial tensile strength (Benmokrane, & Ali, 2016; Robert et al., 2009). However, the design of FRP structures takes into consideration such potential reduction of strength over time by offsetting the initial design strength through the application of an environmental knock-down factor, following the design provisions of AASHTO (2018a) as per equation 1:

$$f_{fd} = C_e f_{fu}^* \qquad (1)$$

Where: f_{fd} is the design tensile strength of FRP; C_e is the environmental reduction factor; and f_{fu}^* is the guaranteed tensile strength of the unconditioned FRP bar. The projected performance over 100 years is meant to be above the minimum design requirement, without the need for reinforcement replacement or additional protection (Figure 3b).

The SS-RC/PC design alternative undergoes the same maintenance criteria as the FRP-RC/PC alternative, given the high corrosion-resistance properties of SS-316/2205 materials (García-Alonso et al., 2007; Ping et al., 1996; Flint & Cox, 1988; and Moser, 2012). The most recent version of the software Life-365 used by the authors, confirms the maintenance-free timeline for SS-RC/PC elements in uncracked concrete. The chloride concentration threshold to initiate corrosion for SS is ten times more than the threshold adopted for CS (Bentz, E., & Thomas, M. D. A., 2018; Srensen, et al., 1990), whereas the propagation period remains the same. Refinement of the propagation period is ongoing under and FDOT research project (Sagues, A. & Mullins, G., 2018). The chloride concentration threshold for SS rebars and strands rises to 11.7 kg/m^3, which is exceeds the calculated chloride concentration projected by Fick's law at 100 years (Figure 4). This means that the maintenance timeline is translated by a number of years that is longer than the SS-RC/PC bridge service life. However, the concrete may still require maintenance over time, as needed for the FRP solution, especially given the assumptions of uncracked concrete. For this reason, the preventive maintenance actions of the SS-RC/PC solution consist of the same timeline and operations required for the FRP-RC/PC alternative. Additionally, the SS-RC/PC solution also allows for the same design criteria as the CS- and ECS-RC/PC counterparts, given the similar mechanical properties of the three materials.

Although pitting corrosion may be a serious problem in some SS reinforcement, causing localized stress concentrating defects (García-Alonso, et al., 2007; Sedrikis, 1996). SS-316 & 2205 alloys have extended pitting corrosion resistance in the presence of chlorides. Also, as the threshold tolerated by SS rebars and strands is 10 times higher than those of CS (Bentz, E., & Thomas, M. D. A., 2018; Srensen, et al., 1990; García-Alonso, et al., 2007), pitting corrosion issues are not triggered for the chloride concentration levels of the specific case study. García-Alonso, et al. (2007) found to be very improbable the pitting corrosion initiation of SS 316 rebars embedded in concrete with chloride additions that were approximately two times the chloride content of the present study. Additionally, the case study of Progreso Pier in Yucatan (Mexico), built between 1937 and 1941 (Arminox, 1999), supports the SS-RC/PC degradation model adopted in this study. Progreso Pier was reinforced with AISI 304 SS rebars (Arminox, 1999), which is a lower grade alloy compared to the that selected for this study.

Figure 5 shows the life cycle stages of the four design alternatives.

6. LCC Analysis

6.1. Material cost

Product stage refers to the fabrication of the reinforcement bars. The product stage cost data of several design alternatives were taken from reports provided by government agencies, private industries and commercial software. For a comparison of these individual costs, see Table 1.

6.1.1. Carbon-steel alternative

CS rebars and strands are generally priced by unit weight. The unit cost of CS rebars is 1.32 USD/kg, and that of CS strands is considered to be 3.30 USD /kg. The cost of the concrete mix for the CS-RC/PC alternative is estimated by adding to traditional concrete mixes the cost of silica fume (HRP) is required to achieve the intended service life. The addition of silica fume to the concrete mix increases the cost of prestressed concrete elements by 19.69 USD/m^3 and increases the cost of cast-in-place elements by 52.32 USD /m^3 (FDOT, 2019).

6.1.2. Epoxy-coated steel alternative

Similar to CS rebars and strands, ECS reinforcement is priced by unit weight. The unit cost of ECS rebars and strands is assumed to be 33% more expensive than CS counterparts. Such a price difference is provided by the software Life-365. In fact, the cost of ECS bars in Life-365 is 1.32 USD/kg, whereas the cost of CS bars is 0.99 USD/kg. Given the fact that these unit costs are dated, the authors applied the calculated difference to the current prices in the U.S. As such, the unit cost of ECS bars is 1.76 USD/kg (whereas the cost of CS bars is 1.32 USD/kg), and that of ECS strands is 4.39 USD/kg (whereas the cost of CS strands is 3.30 USD/kg). With regards to the cost of CS bars and strands, the first author accessed historical steel cost rebars from contractors' past experience and found an average of 1.32 USD/kg as average cost of steel rebar. The unit cost shown is in line with current available estimates and FDOT's publicly accessible reports for historical bid prices (FDOT, 2018b). Similarly to the CS-RC/PC alternative, the ECS-RC/PC solution accounts for the inclusion of silica fume in the concrete mix design.

6.1.3. Stainless-steel alternative

Austenic stainless-steel (SS) alloy 316 was selected as primary reinforcement and duplex 2205 for the prestressing strand in the SS design alternative, to improve the corrosion resistance the aggressive environment for at least a 100-year service life. The unit cost of SS-316 rebars is assumed to be 8.82 USD/kg, as per (FDOT, 2019). Thus, the ratio between CS rebars and SS rebars can be calculated as approximately 6.68. The cost of SS strands, instead, is translated from the unit cost of CS strands, and then multiplied by the cost ratio found between CS rebars and SS rebars. The use of SS as primary reinforcement in corrosive environments may allow the use of traditional concrete mixes in some jursidictions, and the reduction of concrete cover from 76.2 mm to 50.8

mm, for the elements composing the bridge substructure, however for SS prestressed elements in marine environments FDOT still recommends supplemental HRP in the concrete (FDOT, 2018a & 2019).

6.1.4. FRP alternative

GFRP rebars and CFRP strands are priced by unit length. Table 1 shows documented FRP unit cost for the several diameters available. The unit costs of FRP rebars were those from the HRB project. Additionally, similar to the SS-RC/PC alternative, and construction plans, the FRP-RC/PC accounts for a reduced concrete cover of substructure elements and use of conventional concrete mix designs.

6.2. Construction Stage

The costs incurred at the construction stage account for material transport activities from manufacturing plant to site and labor and equipment required for material installation, such as concrete formwork, concrete casting tools, and reinforcement cage installation. All data regarding construction activities were collected during the construction phase of the bridge project. Construction costs of ECS-RC/PC and SS-RC/PC alternatives are shown in Table 2 and Table 3, respectively.

Even though some researchers (Younis et al., 2018; Brown, 2015) account for expected efficiency savings during construction phase of FRP-reinforced projects in LCC analyses, this paper does not take into consideration such potential reduced costs. The costs related to the installation of additional reinforcement equal the savings given by faster and less expensive installation methods for FRP-RC/PC elements, as demonstrated by Cadenazzi et al., 2019b. The design of the FRP-RC/PC solution accounts for more reinforcement because of several FRP properties and current design limitations, such as their lower elastic modulus which negatively affect the deflections and crack widths, and limited creep-rupture resistance properties that affect the long-term performance of the structure. Thus, this paper accounts for the inflated FRP-to-CS reinforcement ratios presented and discussed by (Cadenazzi et al., 2019a).

6.3. Use Stage

The use stage accounts for the maintenance and repair activities of precast/prestressed bearing piles and sheet piles that compose the bridge substructure. Table 4 shows all maintenance operations of the four alternatives and, for convenience, is split into two sections. The first portion of the table shows the absolute costs related to each alternative maintenance operation. The second portion of the table shows the costs breakdown by years of the maintenance and repair activities for each design alternative, conservatively assuming a discount rate of 1%. Costs data were obtained from FDOT historical cost database (FDOT, 2018b).

6.4. End of Life Stage

The EoL stage refers to demolition, disposal, and eventual reconstruction activities of the design alternatives. CS, as well as ECS and SS, are a fully recyclable metals whose scrap can be reconverted to comparable or even higher grades (Broadbent, 2016). This paper accounts for 90% of the original steel quantities to be resold at the end of its life, by considering a price for recycling prepared scrap CS of 0.18 USD/kg (Cadenazzi et al., 2019a). The total steel quantity recycled is an estimated 30,088 USD at EoL.

FRP has complex characteristics that make it a challenging material to be recycled, with research still in progress to address this issue (Dehghan et al., 2017; Correia et al., 2011; Yazdanbakhsh and Bank, 2014). Additionally, no actual pricing for re-use of FRP materials is available to the authors' knowledge. For these reasons, landfill disposal was considered for FRP reinforcement at EoL.

Concrete is estimated to be recycled into roadbeds or RCA (recycled concrete aggregate) (Cadenazzi et al., 2019a). Similarly to CS, 90% of the concrete is assumed to be resold, and the estimated return is 167,633 USD at EoL.

6.5. Net Present Value

As detailed in ISO 15686-5 (ISO 15686-5, 2008), the net present value (NPV) is the sum of all partial costs incurred over the entire life cycle, considering the time value of money, which is calculated in Equation (1).

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} \quad \text{Equation (1)}$$

In (1) C_n is the sum of all cost incurred at a year n; N is the number of periods in the study period; and r is the discount rate. The discount rate is a sensitive factor in the calculation of NPV, as it reflects the value of money over time (Haghani and Yang, 2016). In this paper, a discount rate of 1% was assumed. The selected value is conservatively higher (67%) with respect to the value recommended by the White House Office of Management and Budget (OMB) in circular A-94 (revised November 2017) (White House Office of Management and Budget, 2017) for long-term federal investments (≥30 years). Typical commercial discount rate values for long-term investments range between 1% and 8% (Mistry et al., 2016). The present work considers a public works discount rate of 1%, based on a previous study Cadenazzi et al. (2019a). However, given the influence of the discount rate value over the LCC analysis, a sensitivity analysis is performed for a broad range of values (0%–10%).

7. LCA Analysis

For a deeper investigation of the environmental loading and comparison of several durability-enhancing materials, a Life Cycle Assessment study (LCA) is also included. Scope definition and LCA methods are based on Cadenazzi et al., 2019a. This includes the criteria provided by ISO 14040 (ISO 14040:2006) and ISO 14044 (ISO 14044:2006). The life cycle impact assessment

(LCIA) is based on the methodology "Tool for the Reduction and Assessment of Chemical and other environmental Impacts" (TRACI, version 2.1, 2012), recommended by ISO 21930:2017.

The database Ecoinvent (version 3.4, 2017) was also used as source of secondary data. The impact categories selected for the purposes of comparison are: Ozone Depletion Potential (ODP), Global Warming Potential (GWP 100), Photochemical Oxidant Creation Potential (POCP), Acidification Potential (AP), and Eutrophication Potential (EP). The analysis is performed from cradle-to-gate (raw materials, transportation, and construction) and from cradle-to-grave (raw materials, transportation, construction, maintenance, and EOL). The software used for the analysis is SIMAPRO (version 8.5.2.0, 2018). Cadenazzi et al., 2019a investigated the environmental credentials of the FRP-RC/PC and CS-RC/PC solutions. This paper extends the analysis to the ECS-RC/PC and SS-RC/PC alternatives. Additionally, the accumulation of the major environmental impacts over the life cycle of the bridge for each alternative is included in the analysis.

8. Results and Discussion

The economic and environmental results of the design alternatives are reported independently. Even though recent efforts are aiming to link the LCC and LCA analyses (Moschetti & Brattebø, 2017; Ristimäki et al, 2013), currently there is no available regulation or agreed upon methodology that combines both. In the existing studies, the combined analyses have been predominantly performed for the assessment of residential building projects. Future investigations are required to explore a methodological approach that combines LCC and LCA for infrastructural applications. The findings may be helpful in the decision-making process towards a meaningful combination of environmental and economic assessments in infrastructural projects for selecting the most beneficial scenario.

8.1. LCC

Figure 6 shows the cumulative LCC analysis of the four design alternatives with a spectrum of corrosion-resistant reinforcing materials. As shown in Figure 6 and detailed in Table 5, the NPV of the ECS-RC/PC is only 0.75% lower than that the CS-RC/PC alternative, indicating a limited high cost performance of the former in the long term. Likewise, the SS-RC/PC solution has an NPV which is 10.37% lower than the NPV of the CS-RC/PC alternative, and 9.60% lower than the NPV of the ECS-RC/PC alternative. The FRP-RC/PC solution revealed to be the most cost-effective solution, with an NPV that is approximately 20% lower than that of the CS-RC/PC counterpart. Additionally, the FRP-RC/PC solution has approximately an NPV which is 19.30% and 14.92% lower than the ECS-RC/PC and the SS-RC/PC solutions, respectively. Despite the lower preliminary costs associated with the CS-RC/PC and the ECS-RC/PC, the two most effective corrosion-resistant designs (FRP-RC/PC and SS-RC/PC alternatives) revealed long-term cost savings as they resulted in longer service lives and lower repair costs throughout the analysis period.

FRP-RC/PC revealed to be the optimal solution, with a lower initial investment compared to the SS-RC/PC solution, and a lower NPV in the long term. However, as the market for SS rebars enlarges, and the material becomes more economical and competitive, the SS-RC/PC solution could be an optimal alternative, allowing for the traditional design of RC members, along with all the positive and peculiar aspects of behavior of CS-RC/PC members (in terms of mechanical properties as well as intrinsic recyclability properties).

Additionally, a cost breakdown analysis, based on the selected discount rate (1%), is presented in Figure 7. The construction costs are subdivided into two categories. The construction cost that are dependent of the selection of reinforcement, and the construction costs that are independent of the reinforcing material selected. Despite the lower material-dependent construction costs of the

CS-RC/PC and the ECS-RC/PC design alternatives, the material-independent construction costs are the same for the four alternatives. The latter includes all the costs that are independent from the selection of the reinforcement material, such as: operating expenses; mobilization of equipment and materials; maintenance of traffic devices; temporary barrier walls; quality assurance and quality control; survey activities; bridge temporary works; rip-rap installation; concrete slope pavements; grooving and grinding activities; erosion control; utilities; drainage systems; excavations; embankments; asphalt and concrete flatworks; guardrails installation; signage; and pavement marking, all necessary to complete the bridge.

Finally, Figure 7 shows the cost impacts of maintenance, demolition and reconstruction activities of the four design alternatives. The demolition cost of the SS-RC/PC is slightly lower than the FRP-RC/PC. This is because the recycling of SS at EoL is considered. For the CS-RC/PC and ECS-RC/PC alternatives the demolition and reconstruction activities are combined, as they take place contemporary at year 75 (bridge replacement).

8.2. LCA

Table 6 and Table 7 show the environmental impacts of each design alternative. Table 6 lists the environmental emissions of each design alternative from cradle-to-gate, whereas Table 7 refers to the impacts from cradle-to-grave.

To better visualize the LCA impacts over the service life of the design alternatives, Figure 8 and Figure 9 show the results breakdown by years for two of the most relevant categories and most commonly known, i.e. global warming and photochemical oxidant creation (commonly referred as smog).

As shown in Table 7, the FRP-RC/PC alternative outperforms in four out of five categories the CS-RC/PC and ECS-RC/PC solutions. The only category where the FRP-RC/PC solution is not environmentally competitive is the ozone depletion. However, the impacts are minimal in terms of order of magnitude (the absolute values are in order of decimals), and the reason is strictly correlated to the carbon-fibers outdated database used as data input in the software (Cadenazzi et al., 2019a). Similarly, the SS-RC/PC alternative is well performing in three out of five categories, making it the first competitor to the FRP-RC/PC solution. However, given the great amount of thermal energy needed for the production of stainless-steel rebars and strands, this design alternative has a large contribution in terms of global warming. There is a net difference of 35,508 kg CO_2 eq. between the FRP-RC/PC solution and the SS-RC/PC alternative, making the former option a very appealing choice. Ultimately, the ECS-RC/PC is the least environmental-friendly solution. There is not a single category for which the ECS-RC/PC is an ideal alternative. This is due to the large contribution of the epoxy coated layer needed for the protection of rebars and strands, estimated to be approximately 2,910 liters for the protection of all the bridge reinforcement.

Demolition and landfill activities at EoL contribute to a significant proportion of both carbon and ozone emissions, as shown in Figure 8 and Figure 9. On the other hand, each maintenance activity has very little impact on the overall life-cycle trend, in particular for the FRP-RC/PC and SS-RC/PC solutions. This is due to the fact that maintenance plan of FRP and SS materials do not require major operations (such as cathodic protections or reinforcement replacement), and, thus, do not require traffic disruptions or traffic diversions. Lastly, the reconstruction activities (accounted for one third of the initial construction emissions), contribute to a major portion of the life-cycle emissions of the CS-RC/PC and ECS-RC/PC solutions.

9. Sensitivity Analysis and uncertainty of critical aspects

Since the NPV is affected by the value of the discount rate, a sensitivity analysis is performed and shown in Figure 10, to determine the best solution for each discount rate. The change in the discount rate has minimal effect on the overall NPV of the FRP-RC/PC or SS-RC/PC alternatives, given the low-maintenance costs over time of these two corrosion-resistant solutions. Conversely, the change in discount rate highly affects the CS-RC/PC and the ECS-RC/PC alternatives, which experience relevant maintenance operations over time, and a reconstruction cost. The breakeven point for the FRP-RC/PC cost-effective solution occurs at a discount rate of 4.0% when compared to the CS-RC/PC alternative, and at a discount rate of 4.2% when compared to the ECS-RC/PC alternative. As expected, the FRP-RC/PC solution never intersect the SS-RC/PC curve, to indicate that the solutions are only affected by the initial investment of construction. The breakeven point for the SS-RC/PC cost-effective solution occurs at a discount rate of 2.0% when compared to both the CS-RC/PC and the ECS-RC/PC alternatives. Similarly, the breakeven point of the CS-RC/PC alternative occurs at a discount rate 2.0% when compared to the ECS-RC/PC design. In a scenario where the discount rate is higher than 4.0%, the FRP-RC/PC solution is no more cost-effective. Similarly, in a scenario where the discount rate is higher than 2.0%, the SS-RC/PC solution is no more cost-effective.

Furthermore, in selecting the most effective solution, some additional aspects of uncertainty need to be introduced. For example, the probability that one reinforcement alternative is less costly than another (Eamon et al., 2012), or moreover the changes of chloride concentration over time (Xie et al., 2018). With regards to the reinforcement cost variance over the life-cycle of the bridge, the authors selected a price variance range that goes from minus (-)18% to plus (+)18%. This is based on the price fluctuation of steel during the past 10 years (Figure 11), for which the authors calculated a coefficient of variation of 18% (Figure 11). For this reason, the sensitivity analysis accounts for a price variation of reinforcement that goes from plus or minus (±)18%, for each design alternative. As shown in Table 8, and illustrated in Figure 12, the identified range allows for overlaps at the boundary zones. These boundary zones represent specific scenarios that may influence the final design selection. In the extreme scenario, where the FRP price increases 18%, and the SS price decreases 18%, the SS-RC/PC is the most viable solution. Similarly, if the price of SS rebars increases 18% and the price of CS and ECS rebars decreases 18%, the SS-RC/PC is no more a cost-effective solution. However, any FRP price increment over a CS price decrement, or ECS price decrement would not be sufficient for justifying selection of traditional CS reinforcement rather than SS or FRP corrosion-resistant reinforcement.

Finally, climate change likely contributes to changes in LCC scenarios, too. Xie et al., 2018, with the use of a reliability-based method, evaluated the influence of climate change on the durability of offshore RC bridges considering the acceleration of chloride ion penetration caused by temperature rise (Xie et al., 2018). Xie et al., 2018 estimated a 6% to 15% increase in chloride concentration over 100 years. Adopting the same methodology and the same variation range found by Xie et al., 2018, a chloride concentration variance over time (at depth 76 mm) is presented in Figure 13 for the CS-RC/PC alternative and the ECS-RC/PC.

For the CS-RC/PC and the ECS-RC/PC alternatives, the 6% and 15% increments of chloride concentration over time translates into approximately 6 and 12 months shortening of anticipated maintenance intervals for every maintenance action. In fact, the chloride concentration threshold (1.17 kg/m^3) is reached at year 11.5 and year 11 for increments of 6% and 15%, respectively. In this way, the climate change only affects the timing of intervention. The type of maintenance (amount of material, amount of reinforcement and type of interventions) remains the same. The maintenance activities are only anticipated in years. This fact would have an impact on the preventive maintenance schedule only, affecting thus the costs by means of the discount rate.

As expected, the NPV of the CS-RC/PC alternative is more sensitive to a maintenance schedule change, rather than the ECS-RC/PC solution. This is because the ECS-RC/PC solution requires essential maintenance interventions later in time, when the discount rate has less impact on the LCC. On the other hand, FRP-RC/PC and SS-RC/PC alternatives are not influenced by increment of salient chloride concentrations for values up to 15%. In the case of SS-RC/PC, the upper bound of chloride concentration at year 100 for the increment rate of 15% is still within the acceptable limits for avoiding pitting corrosion. Table 9 and Figure 14 show the LCC results over changes in chloride concentrations.

10.Conclusions

A life-cycle cost comparative analysis of a RC/PC bridge was presented in this paper. A case study was used to validate the proposed model and compare three corrosion-resistant alternatives to a traditional CS-RC/PC solution. The following conclusions can be drawn:

- Despite its relatively low material cost, modelling shows that the ECS is not a cost effective corrosion-resistant solution. As the protective coating layer is damaged or exhibits imperfections, the CS surface is at risk of corrosion and the reinforced structure can rapidly loose its functionality. Thus, for long-term applications in aggressive environments, the use of ECS is not recommended.
- The cost of CS rebars and strands is lower with respect to FRP, SS, and ECS rebars and strands. For this reason, the initial construction cost of the CS-RC/PC alternative is 3.93% lower than the ECS-RC/PC alternative, 8.33% lower than the FRP-RC/PC alternative, and 18.70% lower than the SS-RC/PC alternative.
- The FRP-RC/PC and SS-RC/PC alternatives show economic and environmental benefits over the long term. The net savings associated to the two alternatives are respectively 1,570,670 USD and 814,969 USD, respectively for this example. Conversely, the ECS-

RC/PC alternative shows only 67,085 USD of net savings, which is only 0.85% of the initial investment.

- The SS-RC/PC alternative outperforms in all the impact categories the CS-RC/PC and ECS-RC/PC alternatives. Additionally, the SS-RC/PC solution is performing slightly better than the FRP-RC/PC solution in three out of five categories. However, a substantial net difference between the SS-RC/PC and the FRP-RC/PC alternative in terms of global warming emissions, makes the latter solution more environmental appealing.
- Results are sensitive to the selection of the discount rate. For this reason, a sensitivity analysis was performed. The FRP-RC/PC alternative shows no economic advantage at discount rates higher than 4%. Similarly, the ECS-RC/PC and SS-RC/PC alternatives are not cost-effective when the discount rate is higher than 2%.
- Results are also slightly sensitive to some parameters of uncertainty, such as the reinforcement costs and climate change scenarios. With regards to changes in reinforcement costs in the range of plus or minus ($\pm$)18%, the FRP-RC/PC solution is always the most cost-effective solution when compared to CS-RC/PC and ECS-RC/PC alternatives. However, the SS-RC/PC may become the viable solution if cost of the SS rebars and strands reduces 18%, and cost of the FRP rebars and strands increases 18% from assumed unit rates.

These findings are based on a life-cycle model, durability assumptions, and data that are specific to the case of the Halls River Bridge. Future studies are necessary to determine the cost benefits of other configurations and add more data to the archival literature with regards to the economic and environmental implications of innovative and alternative materials used for reinforced and prestressed concrete structures.

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TABLE 1 – Alternative reinforcement cost comparisons

Reinforcing bars										
	Carbon steel		GFRP		ECS		SS		CFRP	
Bar size	Unit weight [kg/m]	Cost [USD/m]	Unit weight [kg/m]	Cost [USD/m]	Unit weight [kg/m]	Cost [USD/m]	Unit weight [kg/m]	Cost [USD/m]	Unit weight [kg/m]	Cost [USD/m]
M10	0.561	0.75	0.159	1.71	0.561	1.00	0.561	4.93	N/A	N/A
M13	0.996	1.31	0.281	2.36	0.996	1.75	0.996	8.79	N/A	N/A
M16	1.556	2.07	0.427	3.80	1.556	2.75	1.556	13.69	N/A	N/A
M19	2.240	2.95	0.607	4.99	2.240	3.93	2.240	19.71	N/A	N/A
M25	3.982	5.25	1.046	8.56	3.982	6.98	3.982	35.04	N/A	N/A
1x7 15.2mm strand	1.210	3.30	N/A	N/A	1.210	4.39	1.210	22.01	0.221	12.50

TABLE 2 - ECS-RC/PC construction costs

Item	Product stage [A1-A3]	Transport to job site [A4]	Construction [A5]	Total
Sheet piles	USD 935,587	USD 169,200	USD 332,516	USD 1,437,303
Piles	USD 250,292	USD 31,104	USD 223,700	USD 505,097
Bulkhead caps	USD 22,480	Included at product	USD 33,412	USD 55,891
Pier/pier caps	USD 50,222	Included at product	USD 167,577	USD 217,799
Girders	USD 153,111	USD 8,775	USD 115,694	USD 277,580
Deck	USD 126,344	Included at product	USD 269,223	USD 395,568
Approach slabs	USD 29,527	Included at product	USD 59,612	USD 89,139
Traffic railing	USD 20,679	Included at product	USD 24,534	USD 45,213
Gravity wall	USD 3,431	Included at product	USD 23,877	USD 27,309
			Total ECS-RC/PC structures	USD **3,050,897**

TABLE 3 - SS-RC/PC construction costs

Item	Product stage [A1-A3]	Transport to job site [A4]	Construction [A5]	Total
Sheet piling	USD 1,065,371	USD 169,200	USD 332,516	USD 1,567,087
Piling	USD 287,921	USD 31,104	USD 223,700	USD 542,725
Bulkhead caps	USD 46,675	0	USD 33,412	USD 80,087
Pier/pier caps	USD 127,229	0	USD 167,577	USD 294,806
Girders	USD 492,104	USD 8,775	USD 115,694	USD 616,573
Deck	USD 467,548	0	USD 269,223	USD 736,771
Approach slabs	USD 80,774	0	USD 59,612	USD 140,385
Traffic railing	USD 60,943	0	USD 24,534	USD 85,477
Gravity wall	USD 5,735	0	USD 23,877	USD 29,612
			Total SS-RC/PC structures	USD **4,093,525**

TABLE 4 – Maintenance and Repair Costs

Maintenance/Repair activities cost			
Activity	**FRP-RC/PC; SS-RC/PC**	**ECS-RC/PC**	**CS-RC/PC**
Concrete patching	USD 21,781	First time: USD 21,781 Every other year: USD 61,214	USD 61,214
CP1 + bulkhead reinforcement replacement	-	USD 418,340	USD 418,340
CP2	-	USD 274,538	USD 274,538
CP3	-	USD 274,538	USD 274,538
CP1 removal and re-installation + bulkhead reinforcement replacement	-	USD 454,340	USD 454,340
CP2 removal and re-installation		USD 310,538	USD 310,538
Demolition	USD 573,352	USD 573,352	USD 573,352
Reconstruction	-	USD 5,739,842	USD 5,514,278
Recycling	USD 167,633	USD 197,721	USD 197,721
Maintenance/Repair activities cost breakdown by year (discount rate assumed 1%)			
Year	**FRP-RC/PC; SS-RC/PC**	**ECS-RC/PC**	**CS-RC/PC**
11	USD 19,523	USD 19,523	USD 54,867
21	USD 17,674	USD 49,671	USD 49,671
31	USD 16,000	USD 44,966	USD 307,303
41	USD 14,485	USD 40,707	USD 182,569
45	-	USD 267,342	-
51	USD 13,113	-	USD 165,277
55	-	USD 158,828	USD 160,416
56	-	-	USD 260,246
61	USD 11,871		USD 33,361
65	-	USD 143,785	USD 145,223
66	-	-	USD 161,029
70	-	USD 208,465	-
71	USD 10,746	-	USD 30,504
75	-	USD 1,178,986	USD 1,143,337
76	-	(USD 93,745)	(USD 93,745)
81	USD 9,729	-	-
86	-	USD 9,256	USD 26,014
91	USD 8,807	-	
96	-	USD 23,550	USD 23,550
100	USD 211,975	-	-
101	(USD 61,976)	(USD 135,075)	-

Table 5 – LCC results

RESULTS				
	CS-RC/PC BRIDGE	FRP-RC/PC BRIDGE	ECS-RC/PC BRIDGE	SS-RC/PC BRIDGE
Net Present Value (NPV)	USD 7,858,262	USD 6,287,592	USD 7,791,177	USD 7,043,293
Net Saving (NS)		**USD 1,570,670**	**USD 67,085**	**USD 814,969**
Annual Savings (AS)		**USD 15,707**	**USD 670**	**USD 8,149**

Table 6 - Environmental impacts: from-cradle-to-gate scenario

Cradle-to-Gate Results					
Impact category	**Unit of Measure**	**CS-RC/PC**	**ECS-RC/PC**	**FRP-RC/PC**	**SS-RC/PC**
Ozone depletion	kg CFC-11 eq.	0.0844	0.0844	0.5237	0.0886
Global warming	kg CO_2 eq.	1,052,839	1,082,190	1,048,043	1,063,562
Photochemical oxidant creation	kg O_3 eq.	57,960	61,753	66,856	62,543
Acidification	kg SO_2 eq.	4,021	4,213	5,172	4,489

Eutrophication	kg N eq.	2,541	2,569	1,706	2,663

Table 7 - Environmental impacts: from-cradle-to-grave scenario

Cradle-to-Grave Results					
Impact category	**Unit of Measure**	**CS-RC/PC**	**ECS-RC/PC**	**FRP-RC/PC**	**SS-RC/PC**
Ozone depletion	kg CFC-11 eq.	0.1253	0.1253	0.5343	0.1007
Global warming	kg CO_2 eq.	1,475,687	1,512,690	1,091,039	1,126,547
Photochemical oxidant creation	kg O_3 eq.	83,542	88,559	71,666	68,555
Acidification	kg SO_2 eq.	5,682	5,932	5,389	4,786
Eutrophication	kg N eq.	3,510	3,544	1,761	2,749

Table 8 – Sensitivity Analysis: Cost Variance of Reinforcement

SENSITIVITY ANALYSIS - COST VARIANCE OF REINFORCEMENT				
VARIANCE	CS-RC/PC BRIDGE	FRP-RC/PC BRIDGE	ECS-RC/PC BRIDGE	SS-RC/PC BRIDGE
-18%	USD 7,611,362	USD 5,951,446	USD 7,503,676	USD 6,569,119
-15%	USD 7,652,346	USD 6,007,470	USD 7,551,426	USD 6,648,148
-12%	USD 7,693,529	USD 6,063,495	USD 7,599,376	USD 6,727,177
-9%	USD 7,734,712	USD 6,119,519	USD 7,647,326	USD 6,806,206
-6%	USD 7,775,896	USD 6,175,543	USD 7,695,277	USD 6,885,235
-3%	USD 7,817,079	USD 6,231,568	USD 7,743,227	USD 6,964,264
0%	USD 7,858,262	USD 6,287,592	USD 7,791,177	USD 7,043,293
3%	USD 7,899,446	USD 6,343,616	USD 7,839,127	USD 7,122,322
6%	USD 7,940,629	USD 6,399,641	USD 7,887,078	USD 7,201,351
9%	USD 7,981,812	USD 6,455,665	USD 7,935,028	USD 7,280,380
12%	USD 8,022,996	USD 6,511,689	USD 7,982,978	USD 7,359,409
15%	USD 8,064,179	USD 6,567,714	USD 8,030,928	USD 7,438,438
18%	USD 8,105,162	USD 6,623,738	USD 8,078,678	USD 7,517,467
Standard Deviation	**USD 148,461**	**USD 201,999**	**USD 172,859**	**USD 284,943**
Coefficient of Variation	**1.88%**	**3.20%**	**2.21%**	**4.02%**

Table 9 – Sensitivity Analysis: Chloride Concentration

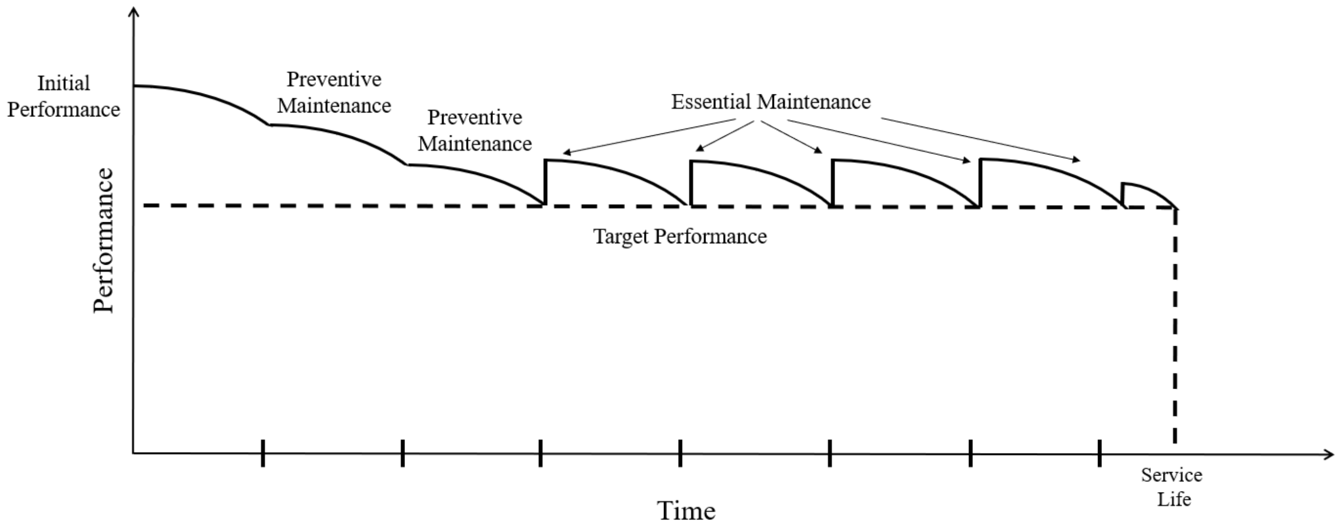
SENSITIVITY ANALYSIS - CHLORIDE CONCENTRATION								
VARIABILITY	CS-RC/PC BRIDGE		FRP-RC/PC BRIDGE		ECS-RC/PC BRIDGE		SS-RC/PC BRIDGE	
0%	USD	7,858,262			USD	7,791,177		
6%	USD	7,869,924	USD	6,287,592	USD	7,801,383	USD	7,043,293
15%	USD	7,881,939			USD	7,811,898		
Cost Range	USD	11,662	-		USD	10,206	-	
Standard Deviation	**USD**	**11,839**	-		USD	**10,361**	-	

Coefficient of Variation	**0.15%**	**0.13%**

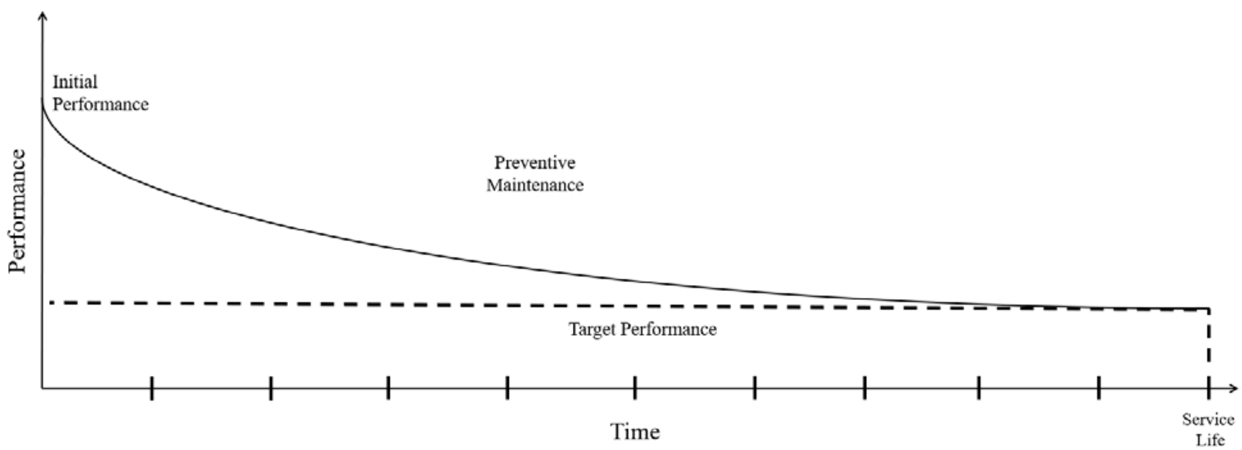
FIGURES

Figure 1 – Halls River Bridge aerial picture as of December 2018

Figure 2 – Chloride concentration threshold at 12 years, for 76.2 mm of concrete cover (a); Chloride Concentration over time at depth 76.2 mm for CS-RC/PC and ECS-RC/PC (b)



(a)



(b)

Figure 3 – Conceptual Durability Performance of CS-RC/PC and ECS-RC/PC solutions (a); Conceptual Durability Performance of FRP-RC/PC and SS-RC/PC solutions (b)

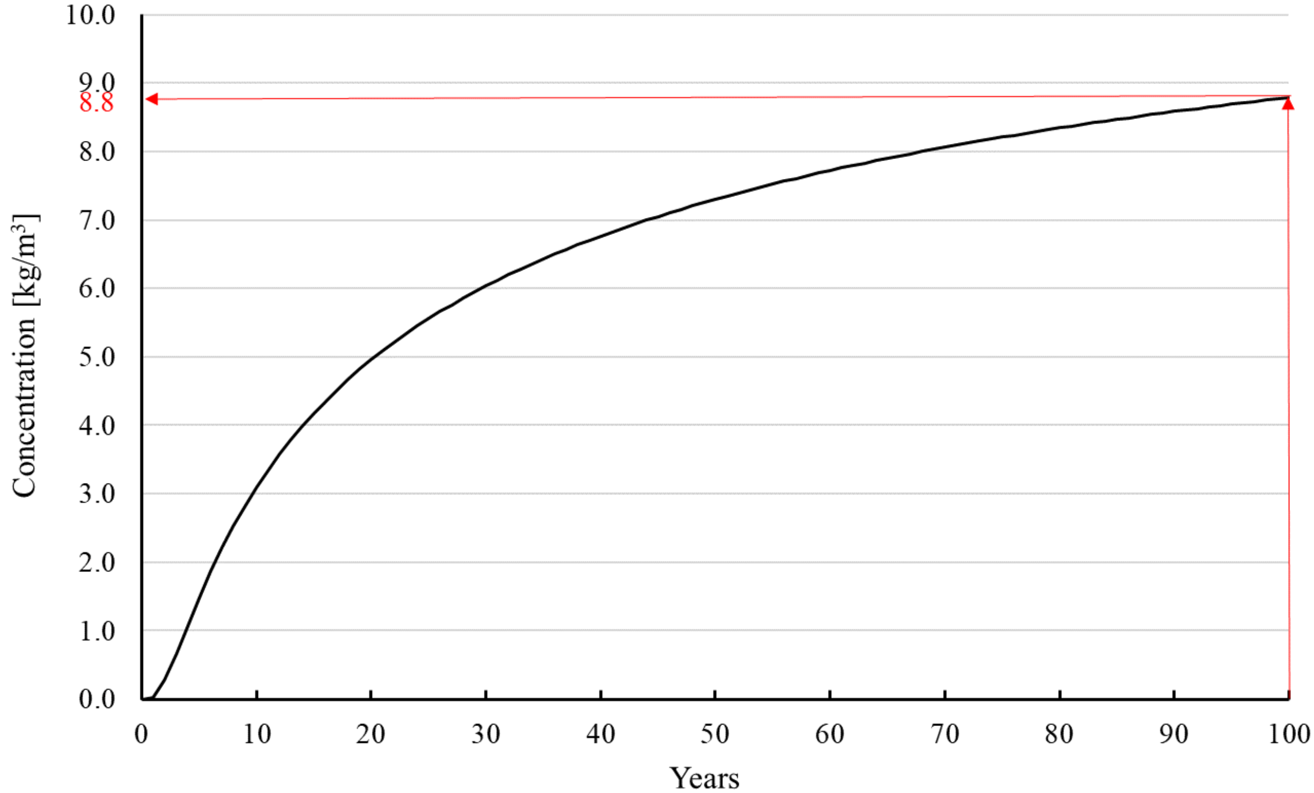


Figure 4 – Chloride Concentration over time at depth 50.8 mm for SS-RC/PC

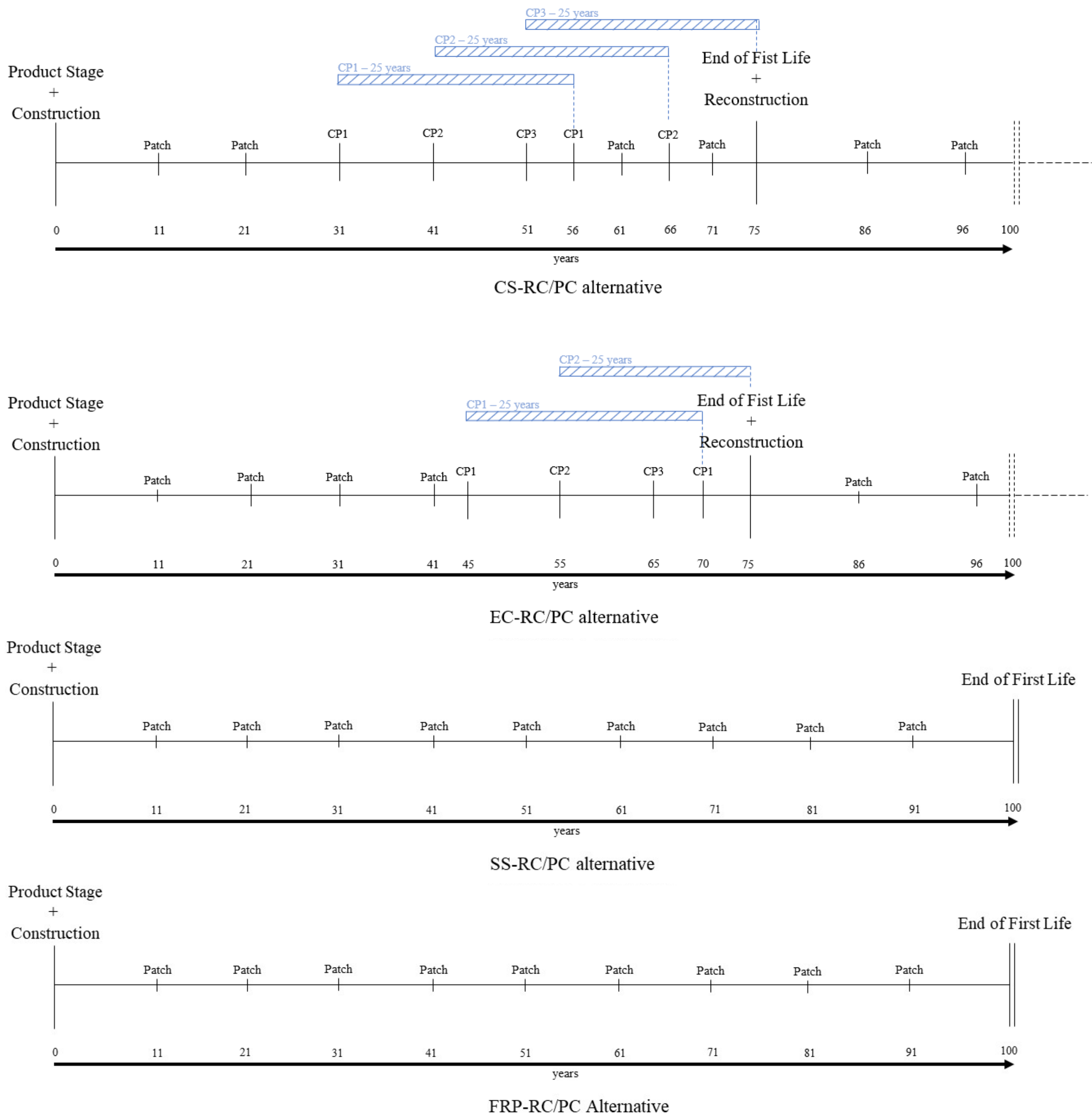


Figure 5 – Life cycle stages of design alternatives

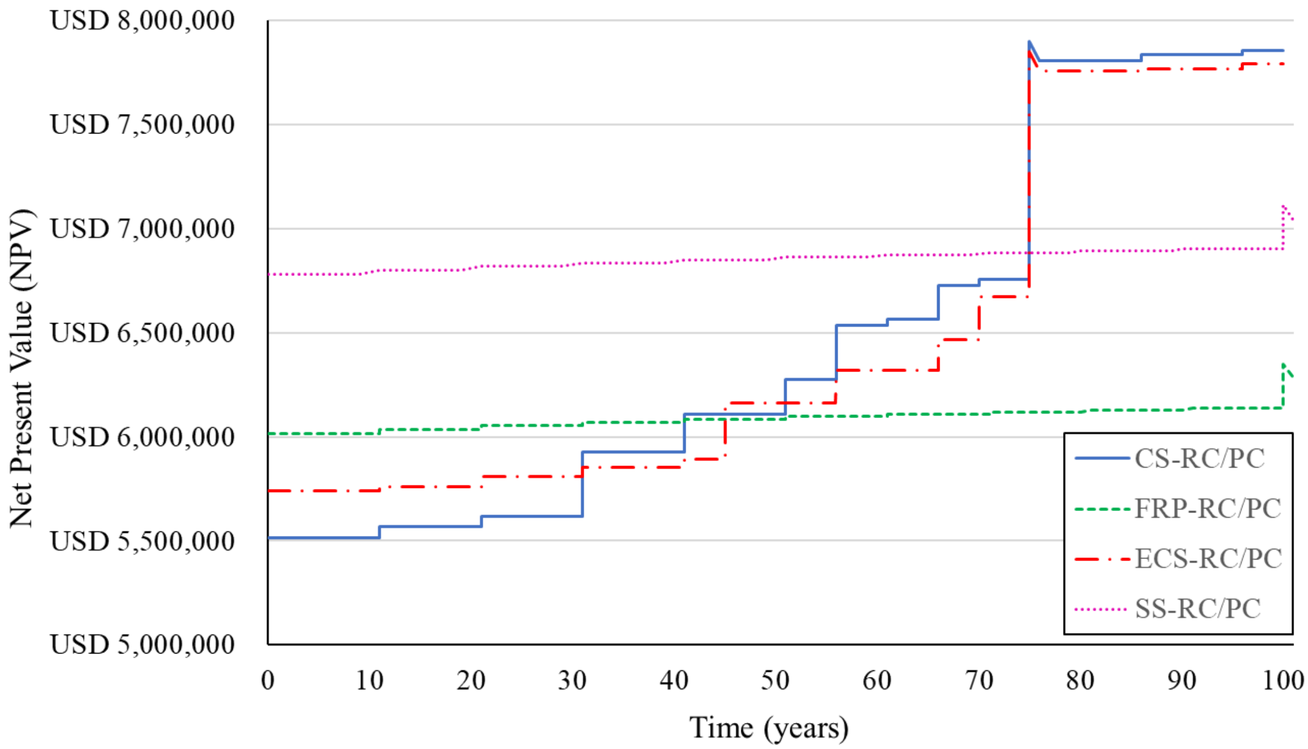


Figure 6 – LCC results considering the baseline scenario where discount rate is 1%

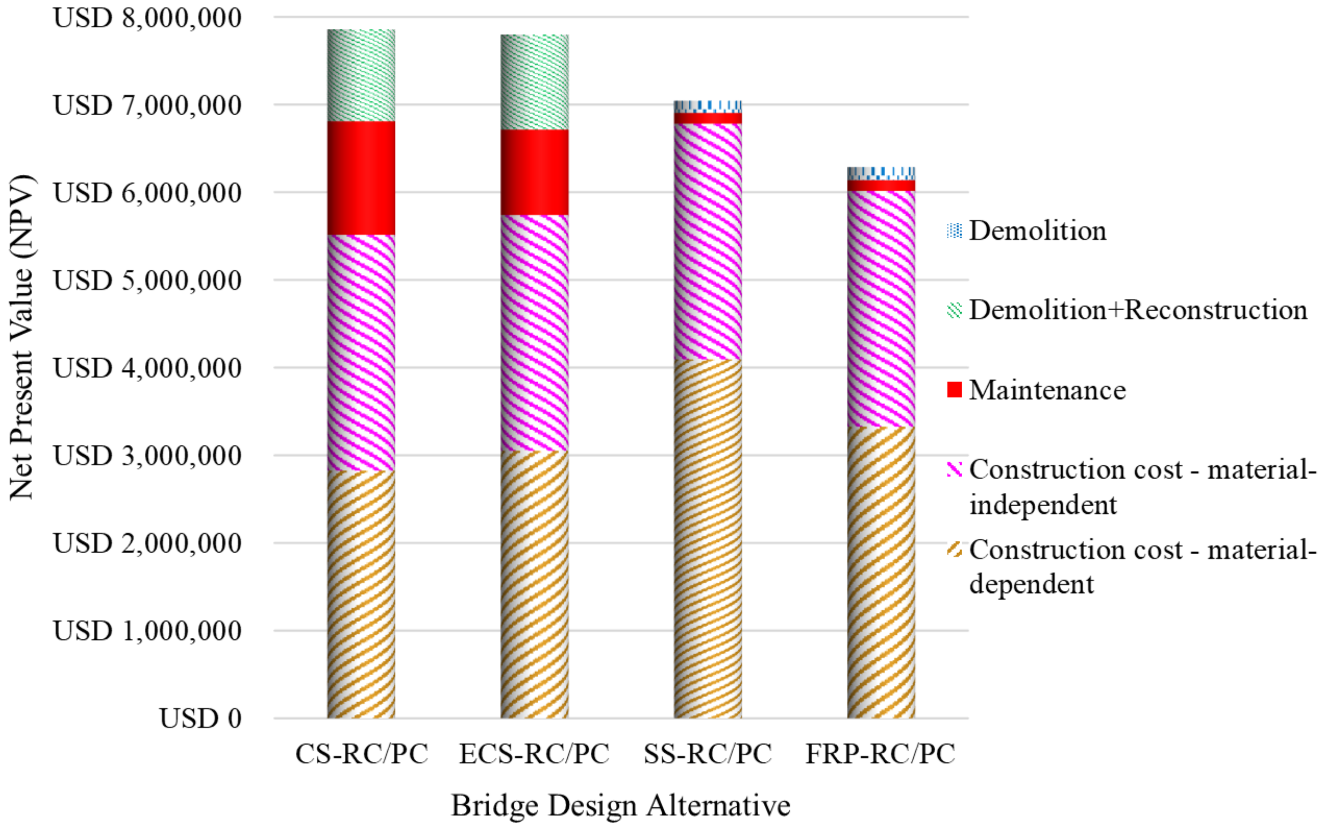


Figure 7 - Breakdown of Life-Cycle Cost for each alternative (discount rate 1%)

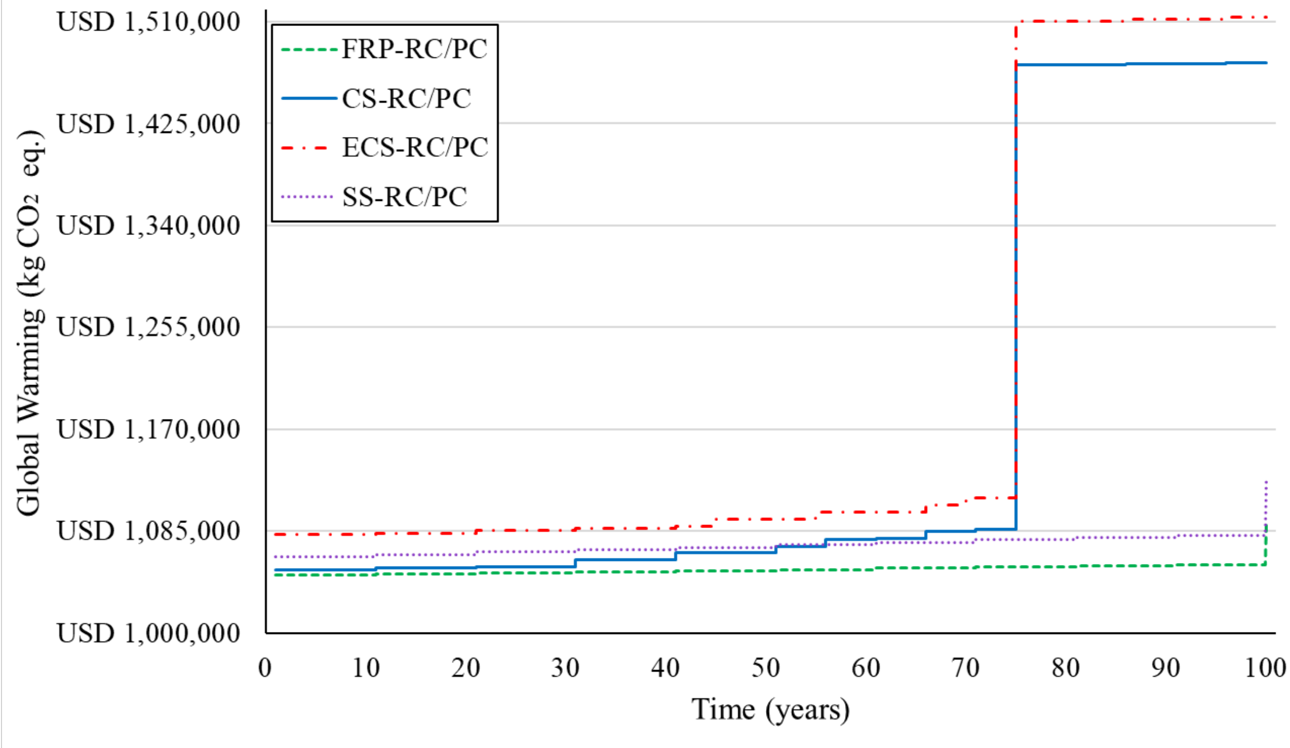


Figure 8 – LCIA results: Global Warming

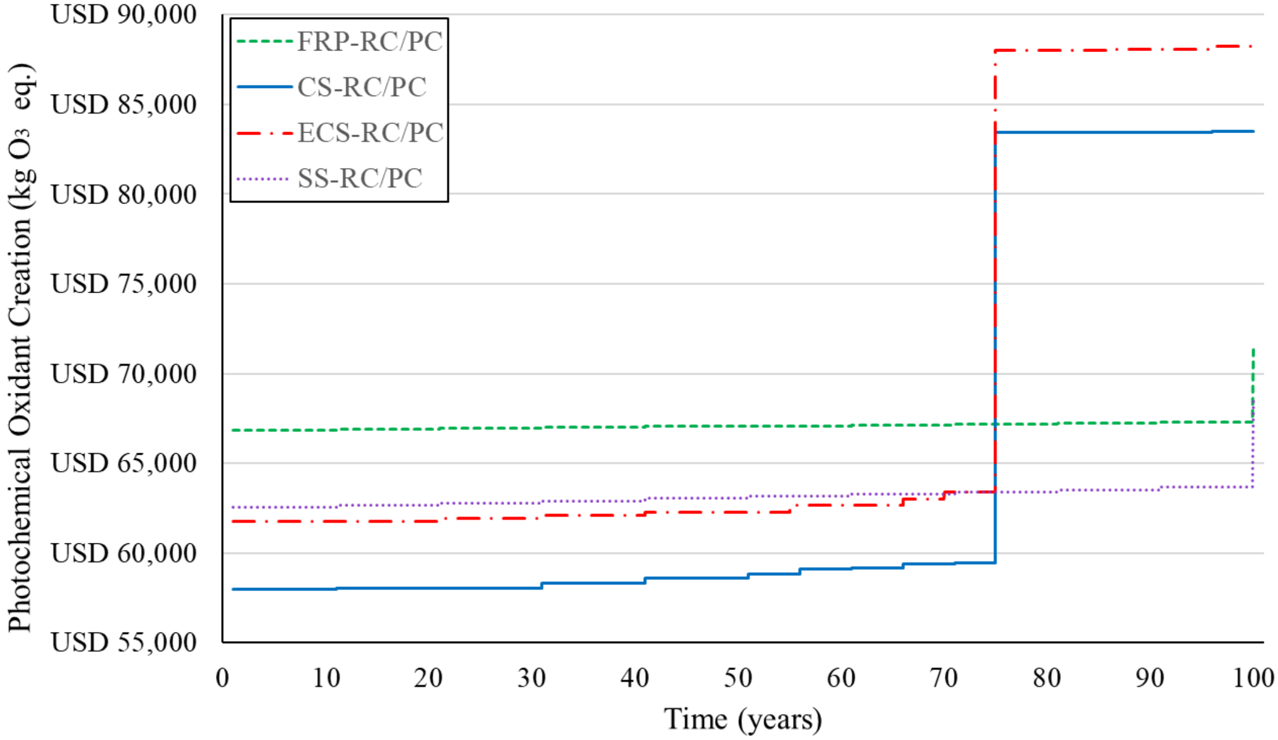


Figure 9 – LCIA results: Photochemical Oxidant Creation

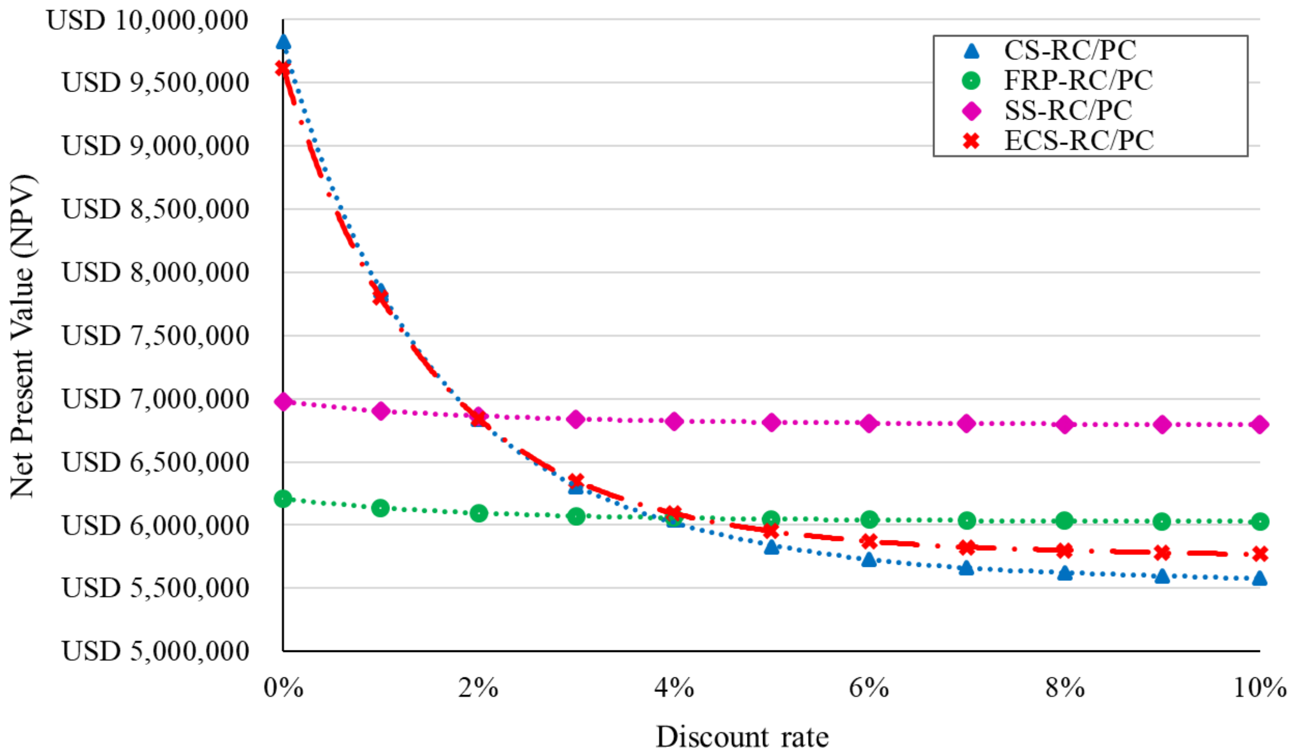


Figure 10 – Sensitivity analysis of LCC results to the discount rate

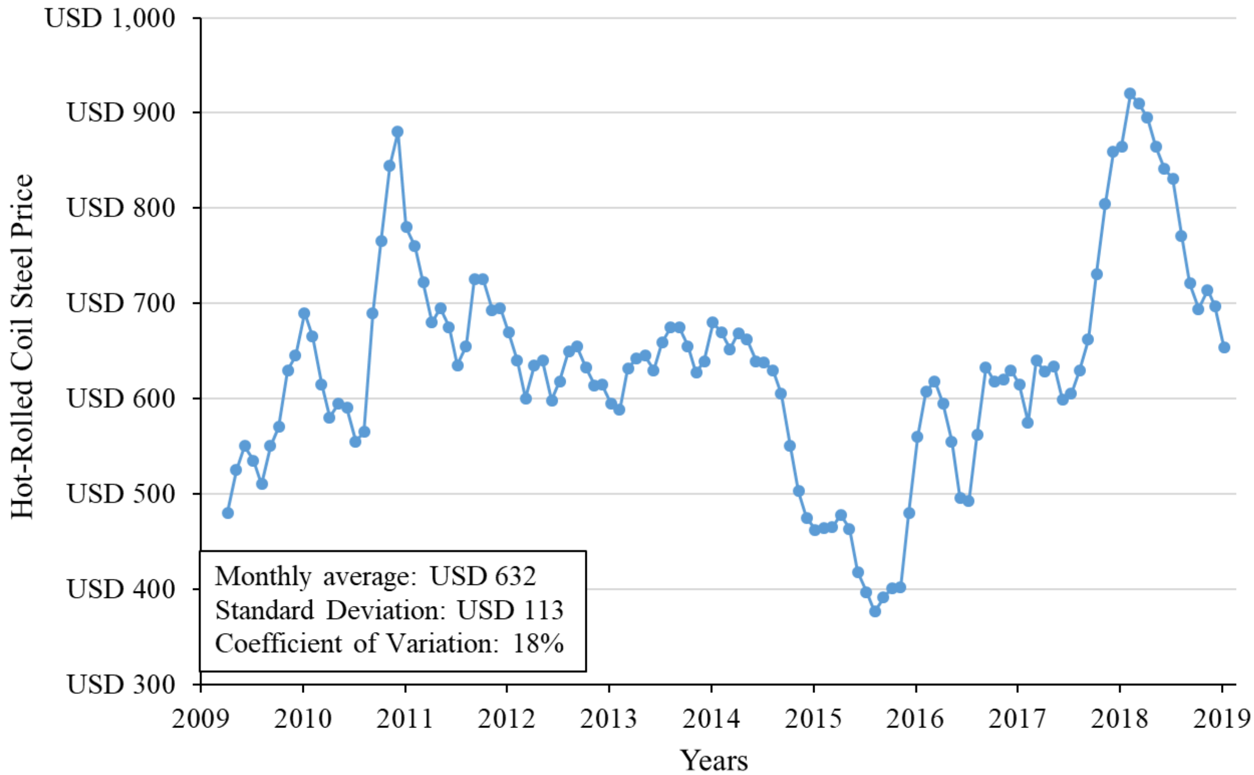


Figure 11 – US Midwest Domestic Hot-Rolled Coil Steel Monthly Price (2009-2019)

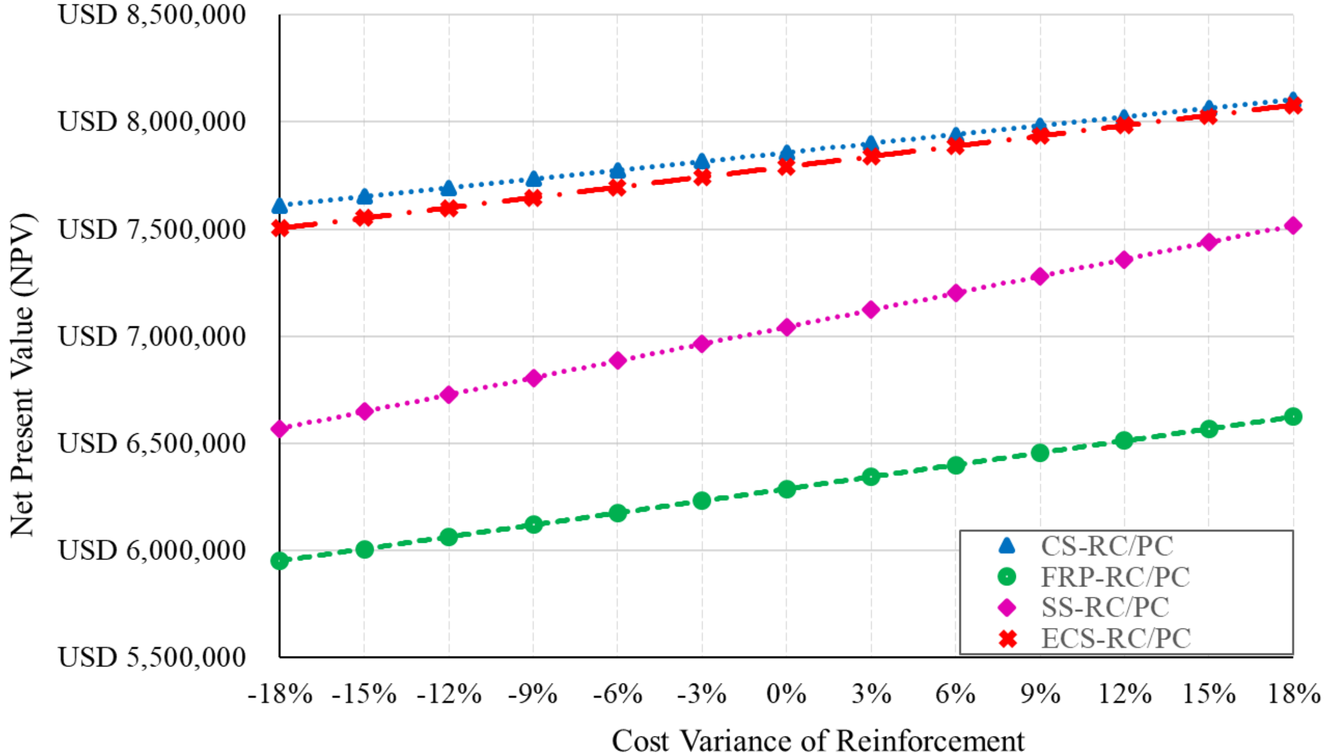


Figure 12 – Sensitivity analysis of LCC results to the Cost of Reinforcement

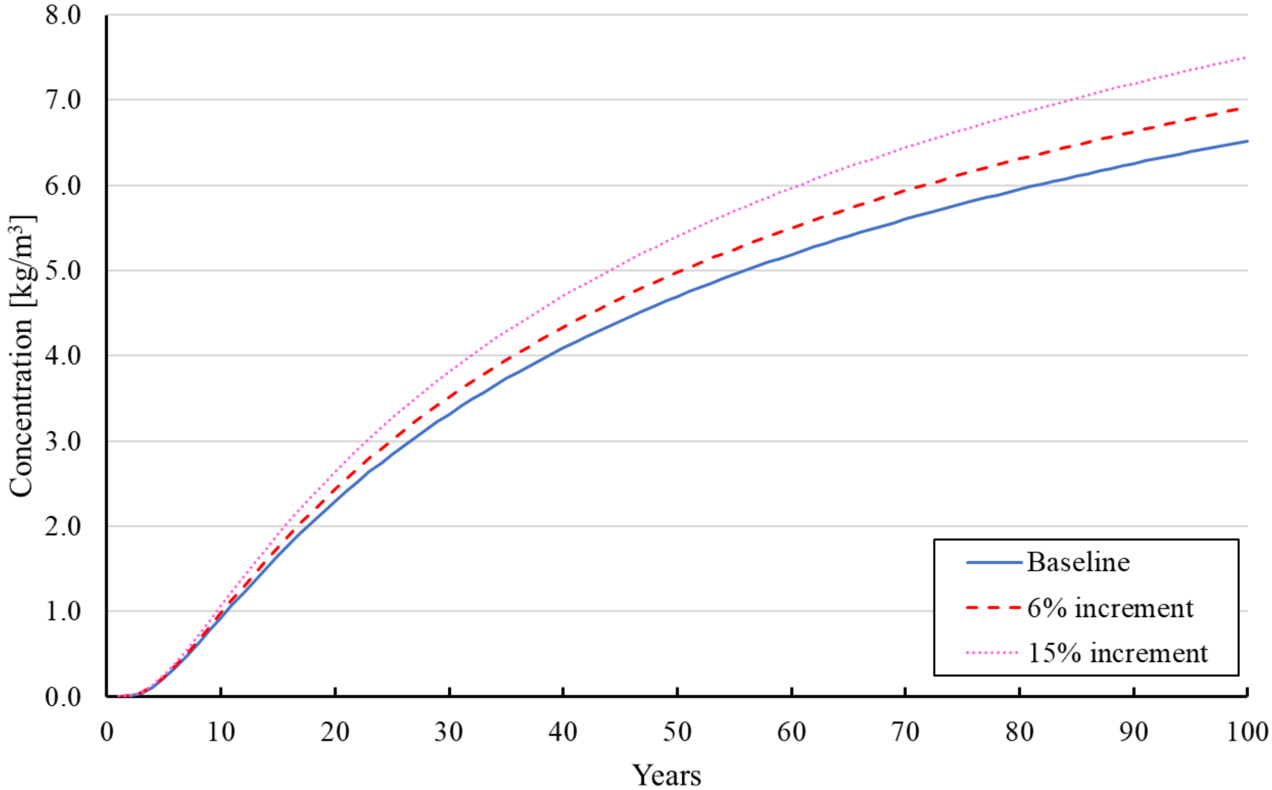


Figure 13 – Variation of Chloride Concentration over time at depth 76.2 mm for CS-RC/PC and ECS-RC/PC

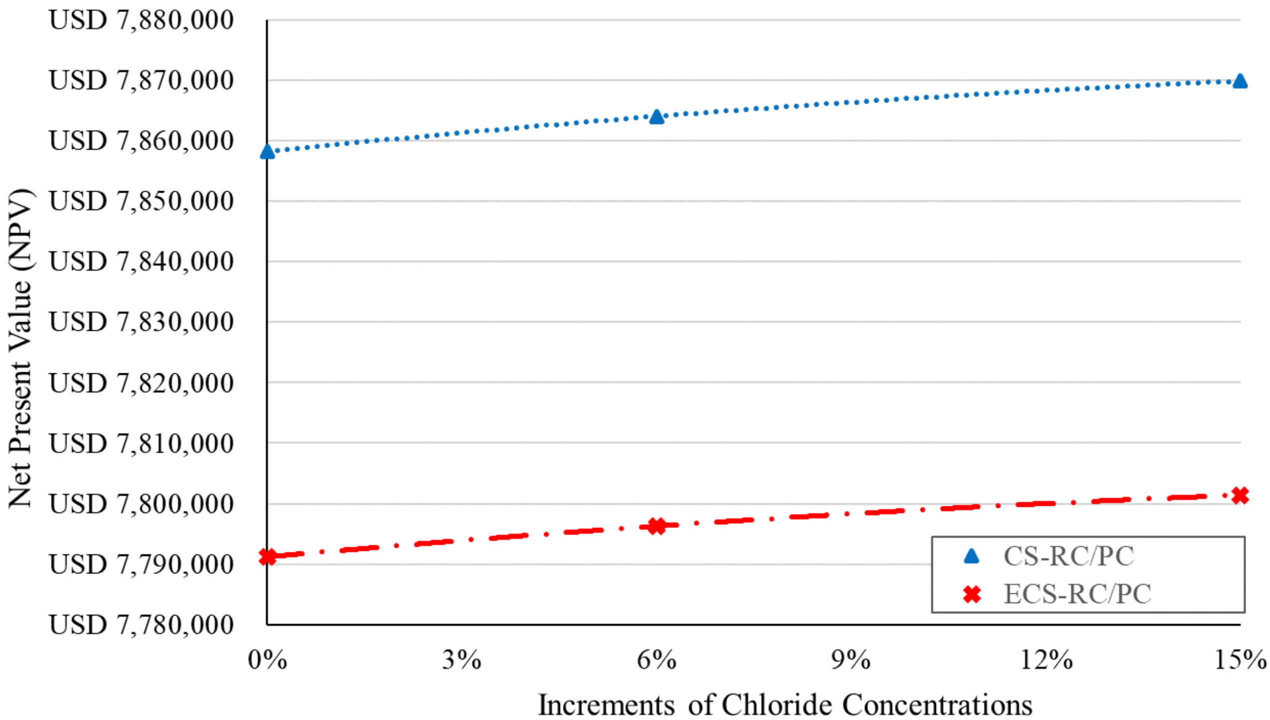


Figure 14 – Sensitivity analysis of LCC results to the Variation of Chloride Concentration