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# Evaluation of probabilistic and deterministic life-cycle cost analyses for concrete bridges exposed to chlorides

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ABSTRACT

Owners and designers are increasingly dealing with infrastructure maintenance to ensure adequate level of performance and functioning required by current standards. Corrosion of reinforcement is one of the major factors that reduces the durability of concrete structures. Fiber reinforced polymers (FRP) have emerged as an effective non-corrosive alternative to traditional steel reinforcement (CS), especially for bridges located in chloride-laden environments. This paper aims to undertake probabilistic and deterministic Life-Cycle Costs (LCC) analyses for: a) an entirely FRP-reinforced concrete bridge; and, b) a conventional reinforced concrete (RC)/ prestressed concrete (PC) bridge; assumed to be located in different corrosion intensity locations of Florida. The deterministic LCC analysis is investigated as a function of varying chloride concentrations for different locations in Florida. A probabilistic analysis is then performed to account for uncertainties in the deterministic model based on a selected coefficient of variation value. For each maintenance intervention, the probabilistic model yields a range of potential effects produced on the LCC by the same cause, ultimately producing more realistic results. The probabilistic model is validated through the input of maintenance and repair cost data from actual in-service bridges. In the probabilistic model, the repair cost is evaluated as a smooth curve, and the results are sensitive to the selection of the coefficient of variation adopted. The probabilistic model allows for better estimation and prediction of the range of long-term LCC behavior of both bridge alternatives. The CS-RC/PC alternative is found to be a high-risk design alternative with higher range (cost spread) and increased LCC. Data available to validate the probabilistic model show a promising match and revealed that the CS-RC/PC alternatives may become costlier earlier in time with a higher degree of probability.

## 1. Introduction

Corrosion of reinforcing steel or other embedded metals in concrete is a major contributor in structural deterioration (Bostanci et al., 2018). presented some promising alternative, sustainable and non-corrosive materials sought to increase the service life of reinforced concrete (RC) and prestressed concrete (PC) structures. Also (Xiao et al., 2017), investigated current status and future opportunities of such alternatives in concrete construction applications. The global annual cost of corrosion damage has been estimated to be approximately $2.5 trillion (Koch et al., 2016) of which approximately 35% is infrastructure related, highlighting the magnitude of the problem. Typically, corroded carbon steel (CS)-RC structural elements are repaired and maintained by using a number of techniques among which externally bonded Fiber Reinforced Polymers (FRP) has become predominant, as investigated by (Nanni, 1995). A realistic assessment of the potential of externally bonded FRP in the strengthening of RC structural members was provided by (Bonacci and Maalej, 2000). Further scholars, such as (Deniaud et al., 2001) investigated through a four-point loading system the shear capacity of RC beams strengthened with externally bonded FRP, showing that FRP strengthening can restore structural capacity to the desired level and can extend the service life of the RC structure. However, externally bonded FRP or equivalent strengthening systems are not always convenient or practically feasible and can also be more expensive compared to preventative strategies. For this reason, the use of non-corrosive internal reinforcement at initial construction may be preferable in order to

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prevent the problems associated with steel corrosion. FRP-RC/PC structures represent a viable solution that may guarantee long-term performance under various aspects (Rossini et al., 2019). investigated the creep rupture strength of GFRP bars (Benmokrane and Ali, 2018). extensively investigated the durability performance of FRPs, as internal reinforcement, under harsh environment conditions. Additionally (Wang and Belarbi, 2013), presented the long-term flexural behaviors of FRP rebars. Glass-FRP (GFRP) and carbon-FRP (CFRP) are the most popular types of FRP bar reinforcement and strands, respectively (Saleh et al., 2019). While both these composites show enhanced mechanical, as presented by (Manickam et al., 2015) and non-corrosive properties, as extensively investigated by (Benmokrane and Ali, 2018), GFRP has a significantly lower cost per unit of tensile strength. This was demonstrated by (Cadenazzi et al., 2019) for a specific RC/PC bridge case study, and by (Younis et al., 2018) for high-rise buildings applications.

Life-Cycle Cost (LCC) analyses are critical tools used to make intelligent engineering economic decisions, allowing owners and designers to look beyond short-term benefits. LCC analyses allow the evaluation of competing design proposals on the basis of total life-cycle cost and allows effective budgeting of future funds. The novelty of this study lies in the following two aspects related to the development of LCC analyses for bridge structures reinforced with FRP bar and strands: firstly, this paper describes and analyzes two LCC models for RC/PC beam bridges exposed to different levels of chlorides (based on location) and include the accuracy of the maintenance period. Since concrete beam bridges are one of the more common types of infrastructure, especially for local road systems and for relatively short spans, this work assumes that similar multi-span beam bridge design can be utilized for other tropical and subtropical areas, exposed to different chloride concentrations. By doing so, it identifies a range of areas geographically for which an FRP-RC/PC bridge design solution would be economically preferable to a conventional CS-RC/PC alternative. Accordingly, new scenarios have been developed for the deterministic LCC analyses leading to the development of a probabilistic methodology that considers a coefficient of variation (COV) for each maintenance action. Secondly, novelty is exhibited via the parametric study that includes the input of historical maintenance data of both CS and FRP-RC bridges validating the proposed model over the LCC curves of the design alternatives. This validation process adds maintenance cost data of FRP-RC to the literature and supports the adequacy of the analysis and methods described in this paper.

The structure of the paper follows: 1) A state-of-the-art section provides background information on the current need of accurate LCC analysis for civil applications. 2) Two bridge design alternatives are presented and the LCC deterministic model is outlined along with the critical parameters associated with each scenario. 3) The probabilistic model (built upon the deterministic model) is described as well as the changes in critical variables in line with the respective scenarios. 4) Results are presented and discussed. 5) The proposed probabilistic model is validated through the input of available historical bridge maintenance data.

## 2. State-of-the-art

Generally, FRP composites are more expensive than traditional Carbon Steel (CS), and this may be one of the factors affecting their currently limited market size. Even though FRP composites have positive long-term economic implications, as shown by (Berg et al., 2006) for a concrete bridge deck case study, as well as by (Cadenazzi et al., 2019a) and (Cadenazzi et al., 2019b) for a bridge case study located in Florida, the lack of rigorous research makes it difficult for practitioners and owners to fully appreciate the potential of FRP reinforcement. In recent years, LCC analyses are becoming an essential tool in the decision-making process of designing bridges, particularly for optimizing the life-time structure effectiveness through reliability-based optimization strategies (Xie et al., 2018). This paper complements existing literature by providing a series of deterministic-based analyses of a bridge case study, under exposure to different chloride concentrations. Deterministic assessments are the basis for probabilistic assessments. Probabilistic LCC assessments aim to investigate the economic credentials in a more accurate manner than conventional deterministic assessments, by better investigating the economic prospects related to uncertainties associated with maintenance schedule, and repair time selection and cost (Lee et al., 2020).

## 3. Deterministic LCC method description

Previous studies, such as (Younis et al., 2018) for high-rise buildings applications, as well as (Cadenazzi et al., 2019) and (Cadenazzi et al., 2019b) for a bridge case study, investigated the LCC of a FRP-RC/PC solution compared to a traditional CS-RC/PC design. The deterministic LCC presented by (Cadenazzi et al., 2019a) and (Cadenazzi et al., 2019b) is based on the bridge design of Halls River Bridge (HRB), the first vehicular bridge that includes FRP materials as main reinforcement in each RC element of the structure, as discussed by (Rossini et al., 2018) and further explained by (Cadenazzi et al., 2020).

The service life of CS-RC/PC design is set at the normal target of 75 years, consistent with (AASHTO, 2020a). The service life of FRP-RC/PC design is set at 100 years, as extensively discussed in (Cadenazzi et al., 2019a) and (Cadenazzi et al., 2019b), consistent with an "enhanced" target service life category in accordance with (AASHTO, 2020b). The enhanced service life category for FRP-RC/PC structures is based upon results obtained from research studies that extrapolate the mechanical and durability behavior of GFRP bars exposed to accelerated alkaline environments up to 100 years. Specifically (Keller et al., 2017), investigated the creep performance of FRPs including the effects given by accelerated alkaline environments, extrapolating behaviors up to 100 years. (fib, 2007) also considers a service up to 100 years for FRP-RC structures. Arguably, FRP-RC/PC could be considered a "Highly corrosion resistant material" under the Class D reinforcing designation in (AASHTO, 2020b), similar to 316LN and 2205 alloy stainless steel. This designation would make FRP-RC/PC eligible for the "extreme" target service life category (150 years), however the authors have made a more conservative selection until extrapolation of fatigue and creep test data can be verified with additional accelerated test data. Conversely, the normal target service life category (75 years) for CS-RC/PC structures is consistent with current practice in the United States (AASHTO, 2020a). The service life selection is based on the deterioration process of concrete structures due to chloride-induced corrosion of the steel reinforcement (Cadenazzi et al., 2019b).

The deterministic LCC approach is based on standards published by EN 15804 (EN, CEN, 2013), and ASTM E2453 (ASTM E2453-19, 2019). LCC considers the costs related to Material Stage, Construction, Maintenance, and End of Life. The alternatives with a shorter service life (75 years) include a cost associated with Reconstruction, accounted in the analysis as a third of the initial construction cost (Cadenazzi et al., 2019a), and a second life (up to 100 years), for comparison of the different alternatives. The selected scenarios differ from each other only with respect to the geographical location and thus exposure to specific amounts of chlorides. For this reason, costs related to Material Stage, Construction, and End of Life are assumed to be the same for each scenario. These costs are based on the HRB case study with regards to the FRP-RC/PC design solution (Cadenazzi et al., 2018), which is the baseline for the costs assumed for the CS-RC/PC alternative. The selected scenarios (that differ as a result of exposure to chlorides) affect only the maintenance schedule of each design alternative. Thus, the costs related to maintenance actions differ case-by-case. The following formula (Equation (1)) is used to calculate the net present value (NPV), which represents the present value of all cash-flows adjusted for the cost of capital and inflation.

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

In equation (1), $C_n$ represents the sum of all cost incurred at a year n (in US dollars), N represents the number of periods in the study period (in years), and r is the discount rate (decimal) to account for the time-value of money.

### 3.1. Maintenance schedule

Maintenance and repair activities refer primarily to the precast/prestressed bearing piles and the seawall elements, that compose the bridge substructure. The software Life-365 (Silica Fume Association, 2017) was used to estimate the schedule of repair activities for the different design alternatives exposed to different chloride levels.

Life-365 estimates the repair schedule of PC and/or RC elements by predicting the corrosion initiation and corrosion propagation periods. The corrosion initiation time represents the time when the chloride concentration threshold is reached at the bar surface. There are a number of studies in the literature that have determined critical chloride contents in CS-RC elements, such as (Al-Saleh, 2015). (Al-Saleh, 2015), as well as (Angst et al., 2009), and (Hussain and Al-Gahtani, 1996) agree on the fact that the critical chloride threshold is highly variable and depends on several factors and specific parameters inherent to test procedures (Angst et al., 2009). Following the EN 206-1 approach, the chloride threshold for the specific case study is set at 1.17 kg/m$^3$. This value has been used in several other studies such as (Bentz and Thomas, 2018), (Lindquist et al., 2006), (Tanaka et al., 2006), (Jin et al., 2010), and (JapanSociety of Civil Engineering, 2007) (Bentz and Thomas, 2018). clearly show how the corrosion propagation period (equal to 6 years) is the time necessary for the corrosion to propagate in the RC/PC element and cause a critical level of damage as manifested by extended concrete spalling or reinforcement cross-section loss for which the capacity of the member becomes insufficient. Also, recent studies such as (Presuel-Moreno et al., 2018) based their analysis on a corrosion propagation period equal to 6 years in a RC element.

With regards to the CS-RC/PC, the deterministic analysis assumes the same maintenance practices considered in the model adopted by prior research (Cadenazzi et al., 2019a). This includes a series of crack repair interventions (minor maintenance), and the installation and maintenance of cathodic protection (CP) for bearing piles, and either CS-reinforcement rehabilitation, or precast element replacement (major maintenance) for the CS-RC/PC solution (Cadenazzi et al., 2019a). By applying minor maintenance on concrete at the corrosion initiation period, the model assumes that the corrosion propagation period is interrupted. This minor maintenance action is conducted in the bridge areas most prone to corrosion (tidal and splash zones), so that the corrosion initiation is delayed and the maintenance interval could restart. However, the model assumes that after two cycles of minor maintenance, the corrosion initiation and propagation period has reached its limit in the more susceptible areas and, therefore, the structure requires a major maintenance intervention (consisting of CP installation for piles and precast element replacement for seawall). Cost estimations for planning of maintenance actions and repairs were obtained from FDOT historical repair costs database and existing inventories (FDOT, 2019), where for bearing piles, minimal patching activities consisting of crack repair interventions costing $ 121 per linear meter, and installation of cathodic protections costing $ 9840 per linear meter. As for the seawall, this paper assumed the following repair activities and costs retrieved from (FDOT, 2019): flowable fill ($ 152.90 per cubic meter), spalled areas restoration with epoxy ($ 13,591 per cubic meter), crack injection and sealing, and non-shrink grout patching for certain areas ($ 5827 per cubic meter). For reinforcing steel replacement, this paper assumed the following activities and costs: removal of corroded bulkhead cap ($ 120 per linear meter), cost of reinforcing steel M13 and M19 ($ 2.54 per kg), concrete class IV ($ 160.25 per cubic meter), removal of existing corner piles ($ 103.81 per linear meter), and installation of new sheet piles ($ 656 per linear meter). All activities include material, labor, and necessary equipment for installation, such as floating turbidity barriers, required in Florida to protect surrounding waters from construction contaminants and to maintain a clean working area.

With regards to the FRP-RC/PC design solution, the maintenance schedule conservatively comprises minimal patching activities ($ 121 per linear meter) on the concrete that take place every 10 years.

### 3.2. End of Life (EOL)

The End of Life (EOL) represents the demolition and disposal stages of the structure. The concrete of both design alternatives is assumed to be recycled. However, FRP materials that currently are commonly made with thermosetting resins, are more challenging to recycle (Correia et al., 2011). Thus, the respective LCC analyses conservatively assume that FRP reinforcement is landfilled, with no profit acquired from FRP recycling, that may be available in the future. It is important to highlight that the EOL of bridge structures is dramatically affected by uncertainty due to the long-life span of bridges. Therefore, the EOL framework is dependent not only on changes in future demolition, disposal and recycling practices and techniques, but also on the bridge service life accuracy and financial discounting assumptions. By altering the bridge service life, the respective EOL costs may change due to variations in NPV. In this paper, the EOL framework is based on the currently available data and the current state-of-art approaches, as per (ASTM E2453-19, 2019). Similarly, to repair and maintenance costs, demolition costs are retrieved from (FDOT, 2019) and assumed to be equal to $ 430 per square meter.

### 3.3. Scenarios

Based on varying levels of naturally occurring chlorides in Florida, three scenarios were identified. A Level 1 scenario, where absence of chlorides or chloride concentration values up to 2.0 kg/m$^3$ at the concrete surface are assumed. This case corresponds to a low chloride concentration scenario, where chloride penetration within the concrete does not reach a critical level that would require major repair of the structure. A medium concentration scenario, namely Level 2, assumes a chloride concentration value of 5.9 kg/m$^3$. For the above-mentioned scenarios, the maximum chloride concentration at concrete surface is reached after 10 years. This suggested build-up period of 10 years is a default value that Life-365 uses to estimate the maintenance schedule of RC/PC structural elements exposed to chlorides (Aldred and Castel, 2014). However, the build-up period can be manually selected in the software. Life-365 suggests lowering the build-up period to 1 year for specific high exposure conditions, such as marine spray zones, where the concrete is subject to spray caused by the action of wind on waves, typical in areas where sea is often rough (Costa and Appleton, 2001). Finally, a high chloride scenario is identified by a chloride concentration value of 23.4 kg/m$^3$ (marine conditions). The high chloride scenario, namely Level 3, coincides with the maximum chloride concentration at concrete surface, reached after 1 year (maximum-chloride scenario, specific for those coastal areas more prone to rough waters). In all cases, a number of interventions (that depends on the level of damage assumed) are required over the service life of both alternatives. With regards to the concrete mix design of the CS-RC/PC alternative, the following variables were defined in Life 365: water/cementitious ratio (w/c): 0.42; concrete cover: 76.2 mm; silica fume: 5%; slag and fly ash: 0%. Supplementary cementitious materials (SCMs), such as fly ash, slag cement (ground granulated blast-furnace slag), and silica fume, are typically added to concrete to reduce its permeability, while increasing its strength and its durability.

The Level 1 scenario consists of minimal maintenance actions due to chloride-induced corrosion. This means that the chlorides reach a

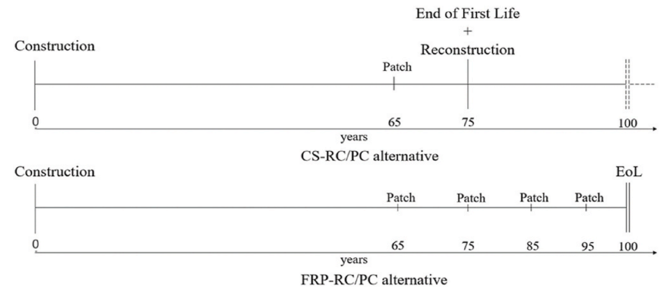


**Fig. 1.** Level 1 scenario maintenance schedule.

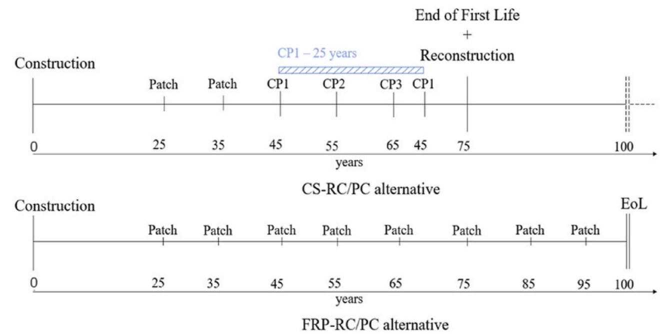


**Fig. 2.** Level 2 scenario maintenance schedule.

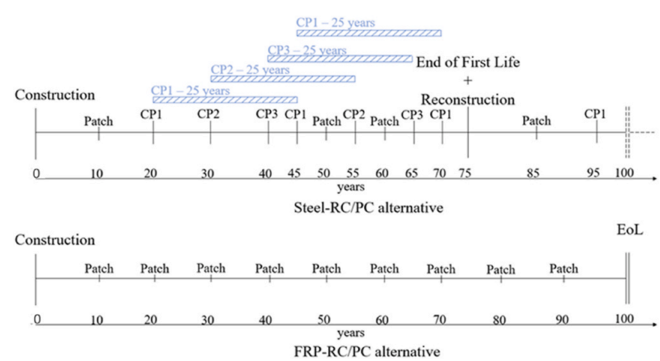


**Fig. 3.** Level 3 scenario maintenance schedule.

critical value that would trigger corrosion of the structure much later in time, at year 65. At year 75, the CS-RC/PC alternative reaches the end of its service life. At the same year when the CS-RC/PC requires minimal maintenance, authors assumed the FRP-RC-PC alternative to undergo minimal concrete patch interventions every 10 years. The patching activities for the FRP-RC/PC alternative are estimated at 33% of the CS-RC/PC design (Cadenazzi et al., 2019a). Fig. 1 shows the service life of the two design alternatives for the Level 1 scenario.

In all cases, the FRP-RC/PC alternative is assumed to undergo minimal concrete patch interventions every 10 years, starting from the year when the CS-RC/PC alternative requires interventions. Fig. 2 shows the service life and the maintenance schedule of the two design alternatives in the Level 2 scenario, where a chloride concentration value of 5.9 kg/m$^3$ is assumed. This exposure scenario translates the repair occurrences by 40 years. It is interesting that an increment of approximately 3.9 kg/m$^3$ chloride impacts considerably the maintenance schedule. This is due to the fact that in this study, the widely used Fick's second law of diffusion (Azad, 1998) has been used to model the chloride ingress in concrete, which is described by a non-linear curve (Cadenazzi et al., 2019b). Given the more severe effects of corrosion into RC-PC elements, the maintenance schedule accounts for interventions requiring CP. After 45 years, CP is needed over 25% of the total number of bridge piles. This protection activity is indicated in Fig. 2 as "CP1". Following, 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 (Cadenazzi et al., 2019a). The authors assumed CP to have a service life of 25 years. For this reason, CP must be periodically replaced. The time frame of each CP replacement is shown in Figure 2, and Fig. 3. At the end of their service life, CP devices 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.

Fig. 3 shows the service life and the maintenance schedule of the two design alternatives in the Level 3 scenario, where a chloride concentration value of 23.4 kg/m$^3$ is assumed within concrete surface after 1 year. Given the severe chloride-induced corrosion under marine conditions for RC-PC elements, CP interventions are anticipated in time and required after only 20 years of service life. Table 1 shows the chloride concentration values for each scenario selected, as well as w/c ratio, concrete cover, and silica fume information for each design alternative.

## 4. Probabilistic LCC model

Probabilistic approaches are widely being considered to address uncertainties of input parameters and their influence on LCC and LCA results (Di Giuseppe et al., 2017): investigated a probabilistic LCC for existing buildings retrofit interventions providing an application example. Similarly (Frangopol et al., 2017), investigated a bridge LCC analysis under uncertain parameters, for a better decision-making process (Harvey et al., 2012). also adopted a probabilistic approach to LCC analyses on flexible pavements applications. (Favi et al., 2018), instead, used a probabilistic approach for a Life-Cycle Assessment study. This paper also implements a probabilistic approach to describe uncertainties related to future maintenance and repair periods. One of the widely accepted methodologies to describe chloride ingress in an RC element, and subsequent deterioration mechanism on an empirical basis, is through the Fick's second law of diffusion, as done by (Zhang et al., 2010), and similarly by (Azad, 1998), even though some scholars (Chatterji, 1995) suggest other combinational modeling approaches to better describe the mechanism. When a specific value of actual chloride concentration at the depth of reinforcement (at time t) is equal to the critical chloride concentration, the structure requires repair. The value of calculated chloride content and critical chloride concentration depends on a number of material properties, such as chloride diffusion coefficient and chloride migration coefficient, environmental variables

**Table 1**
Scenarios.

| Scenarios | Level 1 | | Level 2 | | Level 3 | |
|---|---|---|---|---|---|---|
| | CS-RC/PC | FRP-RC/PC | CS-RC/PC | FRP-RC/PC | CS-RC/PC | FRP-RC/PC |
| Chloride concentration values [kg/m3] | 0–2.0 | | 5.9 | | 23.4 | |
| **w/c ratio** | 0.42 | | 0.42 | | 0.42 | |
| **Concrete cover [mm]** | 76.2 | 50.8 | 76.2 | 50.8 | 76.2 | 50.8 |
| **Silica fume [%]** | 5 | 0 | 5 | 0 | 5 | 0 |

(such as temperature of the structural element or the ambient air), and geometry of the members (Bentz and Thomas, 2018). This concept is adopted in this study when calculating the repair periods in the deterministic analyses. However, there is always a level of uncertainty that needs to be accounted for in the calculation of each parameter. Our approach takes into account uncertainties related to the frequency of each repair time required over the service life of each design alternative. The proposed method assumes each intervention to be modeled as a normal distribution function (NDF), through the application of a coefficient of variation (COV), as shown in Fig. 4. In this way, the proposed approach better refines the deterministic approach by considering a COV to be universally applied to the deterministic LCC stepped curve (Lee et al., 2018).

The adopted COV is based on probabilistic evaluations of corrosion initiation, as done by (Val and Trapper, 2008), and more recently also by (El Houda Cherifi et al., 2019), and durability tests from literature (Micelli and Nanni, 2004). The larger the COV, the larger is the level of uncertainty. In this way, the accuracy of each maintenance period, and the probabilistic cost associated with it can be found.

The probabilistic model applied in this study assumes the probability of $n$ period times to be obtained by the following equation (2). Also, if the cost of first repair time is $C$, then the total repair cost is computed by equation (3) (Jung et al., 2018).

$$P_n = \left(1 - \sum_{k=1}^{n-1} P_k\right) P_n^* \tag{2}$$

$$C_{total} = \sum_{k=1}^{n} k \cdot C \cdot P_k \tag{3}$$

where, $P_n$ is the probability of $n$ times, $C_{total}$ is the total repair time and $C$ is the repair cost.

### 4.1. Coefficient of variation (COV)

Concrete durability can be described as the material capacity to maintain its physical and mechanical properties over time (Loreto et al., 2011). Generally, when considering corrosion, the durability of concrete is assessed using accelerated corrosion tests (Park, 2012). A number of scholars have studied the long-term behavior of RC through accelerated tests. In order to represent the effect of chloride-induced corrosion with a certain level of accuracy, the history of mean values and COVs of chloride penetration values in concrete for long-time exposures are needed. When considering the COV selected for the CS-RC/PC alternatives (Val and Trapper, 2008), conducted probabilistic evaluations of corrosion initiation for CS-RC elements. In this study, COVs of all corrosion-dependent variables were typically 10–30%. Another recent study (El Houda Cherifi et al., 2019) confirms the validity of the range of COVs for traditional RC, by considering the most influential parameters on the variability of the concrete such as the diffusion coefficient and the chloride surface concentration.

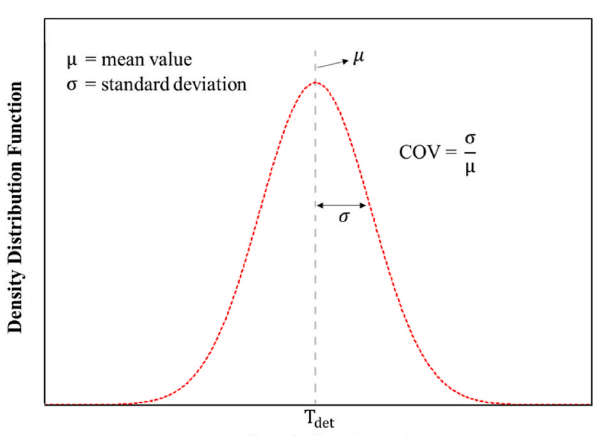


**Fig. 4.** Normal Distribution Function related to timing of repairs.

FRP composites are immune to chloride-induced corrosion. However, they can experience loss of structural performance and degradation in alkali-marine environments, as extensively investigated by (Wei and Weichen, 2011) and in previous works such as (Micelli and Nanni, 2004), with pH above 8.2 (Padan et al., 2005). In this study, the selection of COVs for the FRP-RC/PC solution was based on the COVs describing the retained FRP properties of tensile strength after alkali exposure. The experimental data from (Micelli and Nanni, 2004) was considered to describe the representative COV for the probabilistic analysis. Based on the work by (Micelli and Nanni, 2004), three values of COV are identified, as shown in Table 2–a well-descriptive COV (with respect to the deterministic model) equal to 5%, a fair-descriptive COV equal to 6.4%, and a poor-descriptive COV of 10%, respectively. The value of 6.4% was found to be the mean value of COV for retention in tensile strength tests (loss of strength of accelerated specimens expressed as a percentage of their original strength), whereas the values of 5% and 10% were taken as extreme values.

For the purpose of comparison and for consistency with the COV values used for the FRP-RC/PC alternative, the CS-RC/PC design adopts the same range of COV values. The range of COVs selected is in line with the findings of (El Houda Cherifi et al., 2019) for RC elements, where the value of 10% is taken as uppermost value for projects requiring high quality control.

## 5. Results

The following LCC results are all based on a discount rate of 1%. The selection of the discount rate is based on a number of findings, discussed in (Sokri, 2015), as well as in (Cadenazzi et al., 2019a), and (Cadenazzi et al., 2019b). The whole life-cycle costing is expressed in percentage terms for a better observation and understanding of trends over time. The total life-cycle cost, which considers the future operating costs of the whole project over its lifetime, is set at 100% and it is the maximum cost reached at EOL.

### 5.1. CS-RC/PC alternative

In all scenarios, the initial cost of the CS-RC/PC alternative is 8% lower than the respective FRP-RC/PC alternative (Cadenazzi et al., 2019a). Fig. 5 shows the cumulative Net Present Value (NPV) for the deterministic and probabilistic LCC analyses related to the selected scenarios for the CS-RC/PC alternative. To facilitate the reading and comparison of results, the y-axis in Fig. 5 ranges from 80% (rather than 0%) to 105%. For Fig. 6 and Fig. 7, the y-axis ranges from 70% to 105%, and from 65% to 105%, respectively. At 75 years, the costs of the CS-RC/PC alternative include costs due to demolition activities, and costs of reconstruction (equal to one third of the initial construction which is derived from the remaining evaluation period divided by the target service life of the reconstructed bridge). Additionally, the recycling profits are included at year 76. The profits due to recycling can be easily identified in the deterministic analysis as they reflect sudden drops in costs from values over 100% of the overall LCC. Fig. 5 shows the LCC results of the Level 1 scenario, whereas Fig. 6, and Fig. 7 show the LCC results of the Level 2, and Level 3 respectively.

**Table 2**
COV values.

| Representative Model | COV value (%) |
|---|---|
| Well-descriptive | 5 |
| Fair-descriptive | 6.4 |
| Poor-descriptive | 10 |

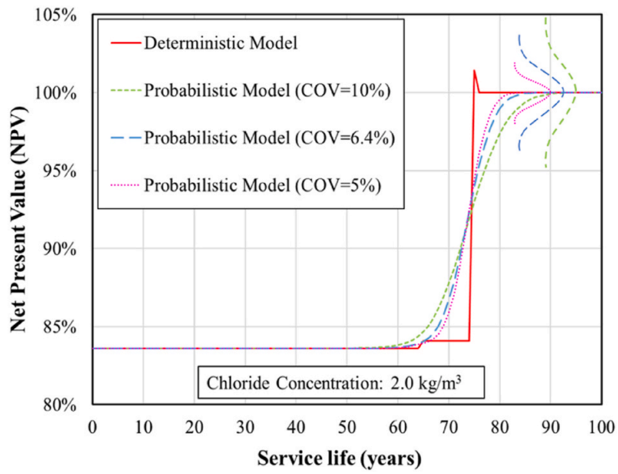


**Fig. 5.** Deterministic and probabilistic LCC results for CS-RC/PC alternative in Level 1 scenario.

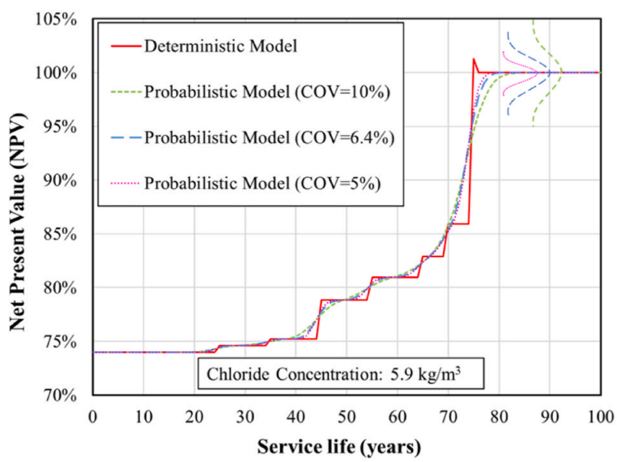


**Fig. 6.** Deterministic and probabilistic LCC results for CS-RC/PC alternative in Level 2 scenario.

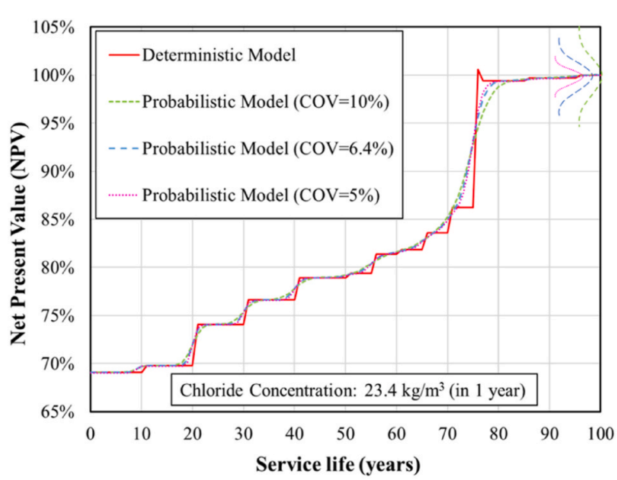


**Fig. 7.** Deterministic and probabilistic LCC results for CS-RC/PC alternative in Level 3 scenario.

In the Level 1 scenario, chloride-induced corrosion is not critical to the point of triggering costly interventions. As maintenance interventions are needed over the service life of the bridge structure (Figs. 6 and 7), the NPV gradually increases. The probabilistic curves, which are the smoothed mean values, better describe the NPV related to each repair action. When the repair action consists of minor maintenance, and thus, the NPV comprises small linear steps, the probabilistic smooth curve is characterized by a lower level of uncertainty, that translates into a slight deviation from the deterministic related line. On the other hand, major maintenance interventions (such as CP, or Demolition and Reconstruction activities) are characterized by a greater level of uncertainty, and the probabilistic smooth curve has a major deviation from the associated deterministic line. The probabilistic cost estimations are adaptive and proactive to the deterministic cost estimations. This means that the costs associated to a specific intervention have a probable cost range that depends on the occurrence and the type of event: when the major contributions to variance are estimated in the deterministic LCC estimations, the uncertainty in repair period across the scenarios is the most important factor driving variation in the cost difference. This variation translates into a curve that accounts for costs prior and after a single deterministic event.

### 5.2. FRP-RC/PC alternative

For all given scenarios, the initial cost of the FRP-RC/PC alternative is assumed to be equal to the FRP-RC/PC bridge cost estimated in (Cadenazzi et al., 2019a), and (Cadenazzi et al., 2019b). Figs. 8–10 show the cumulative NPV for the deterministic and probabilistic LCC analyses related to the selected scenarios for the FRP-RC/PC alternative. To facilitate the reading and comparison of results, the y-axis ranges from 95% (rather than 0%) to 101%. Fig. 8 shows the LCC results of the Level 1 scenario, whereas Figure 9, and Fig. 10 show the LCC results of the Level 2, and Level 3 respectively. Finally, deterministic and probabilistic estimations converge to approximately the same value at EOL as shown in Figs. 8–10.

## 6. Discussion

The general trend shows that there is a good convergence of the probabilistic results at EOL over the deterministic results. This means that the probabilistic model well-describes the uncertainties related to maintenance activities over the alternatives service life.Whereas the deterministic results are shown as step-functions, in which repair interventions are planned with precision beforehand, the probabilistic model allows to account for variability at each repair intervention. This allows to better estimate an optimal maintenance schedule, based on the information available in the short-term. If, for example, the cost associated to the first maintenance were to be higher and ahead of the step function, the RC degraded faster than expected, and a similar trend may

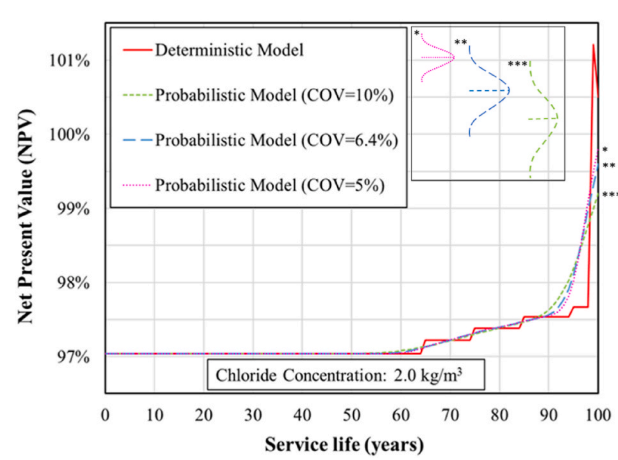


**Fig. 8.** Deterministic and probabilistic LCC results for FRP-RC/PC alternative in Level 1 scenario.

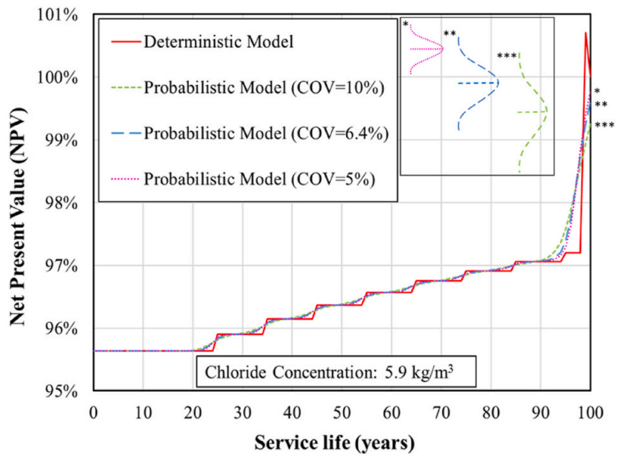


**Fig. 9.** Deterministic and probabilistic LCC results for FRP-RC/PC alternative in Level 2 scenario.

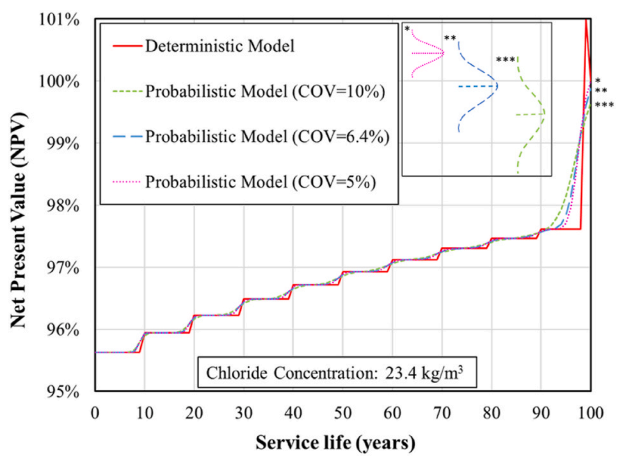


**Fig. 10.** Deterministic and probabilistic LCC results for FRP-RC/PC alternative in Level 3 scenario.

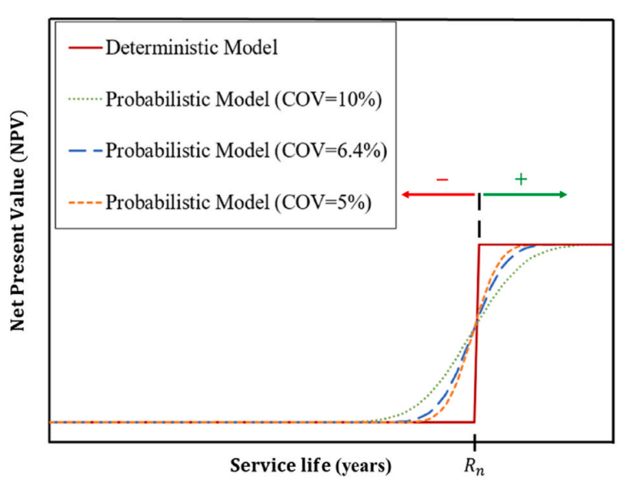


**Fig. 11.** First repair time effect over long-term probabilistic LCC analysis.

be expected for future interventions. Whereas if the costs associated to the first maintenance intervention were to be lower and late in time with respect to the corresponding deterministic step function, owners should expect savings over the long-term. An example of this is shown in Fig. 11, where both deterministic and probabilistic cost curves for a single repair intervention at time n ($R_n$) are presented. Both savings and costs are estimated through the probabilistic results. Thus, it can be said that by applying the probabilistic method proposed in this paper, effective maintenance strategies can be analyzed throughout the service life of the bridge design alternatives.

Furthermore, the probabilistic results revealed that the cumulative distribution function associated to each maintenance intervention for the CS-RC/PC alternative reflects a large cost spread. On the other hand, the FRP-RC/PC alternative is described by a smooth curve that has smaller cost spread, and cost effects of uncertainties related to the degradation of FRP-RC/PC elements that are less impactful on the overall LCC. This is due not to the COV selection that is identical for both alternatives, but it is due to the costs associated to each maintenance intervention, that are greater for the CS-RC/PC alternative and present a great risk of variability due time, escalation and inflation effects.

Finally, changes in the range of selected COV, that reflect variations in quality of concrete for CS-RC/PC bridges, and variations with respect to retained FRP properties of tensile strength after alkali exposure for FRP-RC/PC bridges, have little effect on the total LCC. Results from decreasing COV converge to the deterministic results. The total LCC at EOL vary insignificantly with respect to changes in COV, however the effect of COV becomes critical in understanding the overall maintenance planning, given the information of a single intervention (e.g. the first maintenance intervention). When performing probabilistic analyses at the design stage, a strategic COV selection is of great importance as it may help designers and owners estimate optimal LCC budgets and it may decrease the risk due to uncertainties in material choices.

## 7. Validation of probabilistic model from field data

This paper includes historical maintenance cost data of both CS and FRP-RC bridges. Such data can be useful to validate the proposed probabilistic model over the LCC stepped curves of the real bridge alternatives, so far available. For the purpose of comparison, Fig. 12 shows the probabilistic LCC analysis of the projected bridges along with the deterministic data of the bridges available. The COV selected is equal to 10%, which represents the worst-case scenario of minimum satisfactory concrete quality (generally required in construction projects) for the CS-RC/PC alternative, and poor-descriptive value of FRP retention tensile strength tests for FRP-RC/PC alternatives. Because of the different initial costs of each alternative, the comparison is made in terms of percentages.

As shown in Fig. 12, the available LCC data of FRP-RC bridges, namely Salem Ave Bridge (Foley, 2010) and Thayer Road Bridge (Frosch and Pay, 2006) is limited to 11 and 17 years, respectively. Similarly, the available LCC data of Skyway Bridge (CS-RC bridge) is limited to 33 years. The projected probabilistic smooth curves of both CS-RC/PC and

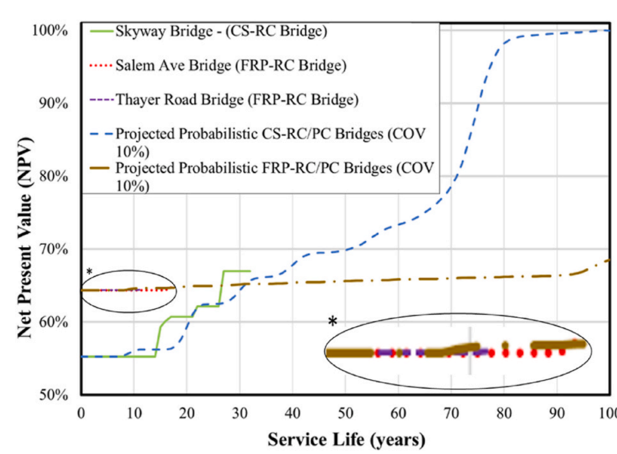


**Fig. 12.** Data validation of projected models on real bridges.

FRP-RC/PC alternatives refer to the Level 3 scenario, which reflects the specific conditions of the case studies. Fig. 12 reveals that there is a good match of the projected probabilistic analysis of the FRP-RC/PC bridges over real data, so far collected. As the probabilistic model revealed, the maintenance cost spread of the FRP-RC/PC bridge alternative is minimal over the entire LCC, and the historical cost data currently available on FRP-RC bridges confirmed this prospect. On the other hand, the projected probabilistic analysis of the CS-RC/PC bridges is slightly conservative compared to the trend of real data so far collected. In the case of CS-RC bridges, there is a strong match from year 0 to year 8, and from year 20 to year 26. Additionally, the cost spread of the CS-RC bridges is greater than the FRP-RC alternatives, as expected. Furthermore, the interpretation of the data reveals that the cumulative distribution function associated with each maintenance intervention for the projected CS-RC/PC alternative is translated ahead in time. This supports the hypothesis that a similar trend may be expected in the future, because the CS-RC elements are degrading faster than initially expected. However, to better understand and more reliably validate the probabilistic model over historical data available, a greater number of bridges and respective historical cost data is needed.

## 8. Conclusions

This paper investigates the economical appeal of two design alternatives for the Halls River Bridge project assumed to be located in different geographical areas of Florida. The two alternatives considered for deterministic and probabilistic model analysis and validations are: an FRP-RC/PC design and a conventional CS-RC/PC design. Based on the HRB experience, design plans, construction data, maintenance and EOL assumptions, deterministic and probabilistic LCC analyses are conducted for both alternatives. The deterministic analyses are estimated for each scenario and a methodology to tackle probabilistic evaluations is developed in order to identify uncertainties correlated to the repair timing, described as normal distribution functions with a variable COV.

Additionally, available cost data of a real CS-RC bridge subject to corrosion and available cost data of two real FRP-RC bridges, were used to compare the projected LCC analyses with actual LCC data. Based on the results obtained, the following can be concluded:

- When the probabilistic LCC maintenance model is applied, the repair cost is evaluated as a smooth curve, unlike the deterministic model. The probabilistic LCC outputs are sensitive to the choice of the selected COV. The lower the COV, the closer the smooth curve is to the deterministic stepped curve.
- The probabilistic model allows to better estimate and predict the long-term LCC behavior of bridges by extrapolating information from the short-term. In this way, effective maintenance strategies can be obtained through probabilistic analyses. With changes in COV, which reflect uncertainties related to the degradation mechanism of both CS-RC/PC and FRP-RC/PC alternatives, the maintenance cost may vary over time and the study of its trend becomes key to effective maintenance planning and understanding future cost implications.
- The FRP-RC/PC solution reduces the long-term cost of the structure. Based on a 100-year study period and 1% discount rate, the LCC spread of the FRP-RC/PC design is more concentrated than the CS-RC/PC alternative, implying more financial reliability. Additionally, the data validation revealed that the FRP-RC/PC alternatives may be become more cost-efficient earlier in the service life of the structure.
- The CS-RC/PC solution is generally a high-risk design alternative with higher cost spread and increased LCC. Data validation revealed that the CS-RC/PC alternatives may be become costlier earlier in the service life of the structure.
- The validation of the projected models on available historical bridge data showed a promising match. However, more data is needed before drawing overarching conclusions.

## Data availability statement

The probabilistic model used during the study is available in a repository online in accordance with funder data retention policies. In particular, details with regards to the probabilistic model are explained by Lee et al. (2018) and can be retrieved online at: https://doi.org/10.5659/JAIK_SC.2018.34.2.41.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## References

Aashto, 2020a. AASHTO LRFD Bridge Design Specifications, ninth ed. American Association of Highway and Transportation Officials), Washington, DC.
Aashto, 2020b. Guide Specifications for the Service Life Design of Highway Bridges, first ed. American Association of Highway and Transportation Officials). Pending publication, Washington, DC.
Astm E2453-19, 2019. Standard Practice for Estimating the Life-Cycle Cost of Ownership of Property Assets. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/E2453-19. https://www.astm.org/.
Aldred, J.M., Castel, A., 2014. Chloride penetration after field exposure compared with estimates from service life prediction models. In: Proceedings of the RILEM International Workshop on Performance-Based Specification and Control of Concrete Durability, pp. 143–150, 11 - 13 June 2014, Zagreb, Croatia.
Al-Saleh, S.A., 2015. Analysis of total chloride content in concrete. Case Studies in Construction Materials 3, 78–82. https://doi.org/10.1016/j.cscm.2015.06.001.
Angst, U., Elsener, B., Larsen, C.K., Vennesland, Ø., 2009. Critical chloride content in reinforced concrete—a review. Cement Concr. Res. 39 (12), 1122–1138.
Azad, A.K., 1998. Chloride diffusion in concrete and its impact on corrosion of reinforcement. In: Proceedings of Symposium on Performance of Concrete Structures in the Arabian Gulf Environment, pp. 262–273. https://doi.org/10.1007/s40069-014-0095-y.
Benmokrane, B., Ali, A.H., 2018. Durability and long-term performance of fiber-reinforced polymer as a new civil engineering material. In: International Congress on Polymers in Concrete. Springer, Cham, pp. 49–59.
Bentz, E., Thomas, M.D.A., 2018. Life-365 Service Life Prediction Model and Computer Program for Predicting the Service Life and Life-Cycle Cost of Reinforced Concrete Exposed to Chlorides. Version 2.2.3. Silica Fume Association.
Berg, A.C., Bank, L.C., Oliva, M.G., Russell, J.S., 2006. Construction and cost analysis of an FRP reinforced concrete bridge deck. Construct. Build. Mater. 20 (8), 515–526. https://doi.org/10.1016/j.conbuildmat.2005.02.007.
Bonacci, J.F., Maalej, M., 2000. Externally bonded fiber-reinforced polymer for rehabilitation of corrosion damaged concrete beams. Structural Journal 97 (5), 703–711.
Bostanci, S.C., Limbachiya, M., Kew, H., 2018. Use of recycled aggregates for low carbon and cost effective concrete construction. J. Clean. Prod. 189, 176–196. https://doi.org/10.1016/J.JCLEPRO.2018.04.090.
Cadenazzi, T., Dotelli, G., Rossini, M., Nolan, S., Nanni, A., 2019a. Life-cycle cost and life-cycle assessment analysis at the design stage of a fiber-reinforced polymer-reinforced concrete bridge in Florida. Advances in Civil Engineering Materials 8 (2), 128–151. https://doi.org/10.1520/ACEM20180113.
Cadenazzi, T., Dotelli, G., Rossini, M., Nolan, S., Nanni, A., 2019b. Cost and environmental analyses of reinforcement alternatives for a concrete bridge. Structure and Infrastructure Engineering 1–16. https://doi.org/10.1080/15732479.2019.1662066.
Cadenazzi, T., Nolan, S., Mazzocchi, G., Stringer, Z., Nanni, A., 2020. Bridge case study: what a contractor needs to know on an FRP reinforcement project. J. Compos.

Construct. 24 (2), 05020001 https://doi.org/10.1061/(ASCE)CC.1943-5614.0000998.
Cadenazzi, T., Rossini, M., Nolan, S., Dotelli, G., Arrigoni, A., Nanni, A., 2019. Resilience and economical sustainability of a FRP reinforced concrete bridge in Florida: LCC analysis at the design stage. In: 6th International Symposium on Life-Cycle Civil Engineering, IALCCE 2018. CRC Press/Balkema, pp. 2913–2920.
Chatterji, S., 1995. On the applicability of Fick's second law to chloride ion migration through Portland cement concrete. Cement Concr. Res. 25 (2), 299–303. https://doi.org/10.1016/0008-8846(95)00013-5.
Correia, João R., Almeida, Nuno M., João R. Figueira, 2011. Recycling of FRP composites: reusing fine GFRP waste in concrete mixtures. J. Clean. Prod. 19 (15), 1745–1753. https://doi.org/10.1016/j.jclepro.2011.05.018.
Costa, A., Appleton, J., 2001. Concrete carbonation and chloride penetration. Concrete Science and Engineering 3, 242–249. ISSN 1295-2826/01.
Deniaud, C., Cheng, J.R., 2001. Shear behavior of reinforced concrete T-beams with externally bonded fiber-reinforced polymer sheets. Structural Journal 98 (3), 386–394.
Di Giuseppe, E., Iannaccone, M., Telloni, M., D'Orazio, M., Di Perna, C., 2017. Probabilistic life cycle costing of existing buildings retrofit interventions towards nZE target: methodology and application example. Energy Build. 144, 416–432. https://doi.org/10.1016/j.enbuild.2017.03.055.
El Houda Cherifi, W.N., Houmadi, Y., Benali, O., 2019. Probabilistic analysis for estimation of the initiation time of corrosion. Math. Model Civ. Eng. 15 (2) https://doi.org/10.2478/MMCE-2019-0004.
En 206-1, 2000. European Standard. Concrete — Part 1: Specification, Performance, Production and Conformity European Committee for Standardization.
Favi, C., Di Giuseppe, E., D'Orazio, M., Rossi, M., Germani, M., 2018. Building retrofit measures and design: a probabilistic approach for LCA. Sustainability 10 (10), 3655. https://doi.org/10.3390/su10103655.
Fdot, 2019. Historical Cost and Other Information. Direct Link to 2018 Annual Statewide Average. Historical Cost Landing Page. https://perma.cc/BAY4-NEKF. https://perma.cc/GW7Z-NVBP.
fib, 2007. FRP Reinforcement in RC Structures, Bulletin, vol. 40. International Federation for Structural Concrete, Lausanne, Switzerland, pp. 1–151. https://doi.org/10.35789/fib.BULL.0040.
Foley, C.M., 2010. In-Situ Monitoring and Testing of IBRC Bridges in Wisconsin. Wisconsin Highway Research Program. Technical Report. Marquette University.
Frangopol, D.M., Dong, Y., Sabatino, S., 2017. Bridge life-cycle performance and cost: analysis, prediction, optimisation and decision-making. Structure and Infrastructure Engineering 13 (10), 1239–1257. https://doi.org/10.1080/15732479.2016.1267772.
Frosch, R.J., Pay, A.C., 2006. Implementation of a non-metallic reinforced bridge deck. In: Thayer Road Bridge. Publication FHWA/IN/JTRP-2006/15-2. Joint Transportation Research Program, vol. 2. Indiana Department of Transportation and Purdue University, West Lafayette, Indiana. https://doi.org/10.5703/1288284314223.
Harvey, J.T., Rezaei, A., Lee, C., 2012. Probabilistic approach to life-cycle cost analysis of preventive maintenance strategies on flexible pavements. Transport. Res. Rec. 2292 (1), 61–72. https://doi.org/10.3141/2292-08.
Hussain, S.E., Al-Gahtani, A.S., 1996. Chloride threshold for corrosion of reinforcement in concrete. Materials Journal 93 (6), 534–538.
Japan Society of Civil Engineering, JSCE, 2007. Standard Specification for Concrete Structures—Materials and Construction. JSCE-Guidelines for Concrete 16. Japan Society of Civil Engineering (JSCE), Tokyo, 978-4-8106-0752-9.
Jin, W.L., Yan, Y.D., Wang, H.L., 2010. Chloride Diffusion in the Cracked Concrete. Fracture Mechanics of Concrete and Concrete Structures-Assessment, Durability, Monitoring and Retrofitting, vols. 880–886, ISBN 978-89-5708-181-5.
Jung, S.H., Yang, H.M., Yang, K.H., Kwon, S.J., 2018. Maintenance for repaired RC column exposed to chloride attack based on probability distribution of service life. International Journal of Concrete Structures and Materials 12 (1), 22. https://doi.org/10.1186/s40069-018-0259-2.
Keller, M., Schultz-Cornelius, M., Pahn, M., 2017. Synergistic Effects of Alkaline Environment on the Behavior of GFRP Bars under Sustained Load (Paper Presentation, CDCC 2017 Fifth International Conference on Durability of FRP Composite for Construction and Rehabilitation of Structures. Sherbrooke, Canada.
Koch, G., Varney, J., Thompson, N., Moghissi, O., Gould, M., Payer, J., 2016. International Measures of Prevention, Application, and Economics of Corrosion Technologies Study (IMPACT). NACE International.
Lee, H., Lee, H.S., Suraneni, P., Singh, J.K., Mandal, S., 2020. Prediction of service life and evaluation of probabilistic life-cycle cost for surface-repaired carbonated concrete. J. Mater. Civ. Eng. 32 (10), 04020297 https://doi.org/10.1061/(ASCE)MT.1943-5533.0003390.
Lee, H., Yang, H., Lee, H.S., 2018. Probabilistic LCC evaluation for surface repair of carbonated rc structure. Journal of the Architectural Institute of Korea Structure and Construction 338, 41–48. https://doi.org/10.5659/JAIK_SC.2018.34.2.41 (in Korean), 34 2.
Lindquist, W.D., Darwin, D., Browning, J.P., Miller, G.G., 2006. Effect of cracking on chloride content in concrete bridge decks. ACI Mater. J. 103 (6), 467–473. URI: http://hdl.handle.net/1808/23334.
Loreto, G., Di Benedetti, M., Iovino, R., Nanni, A., Gonzalez, M.A., 2011. Evaluation of corrosion effect in reinforced concrete by chloride exposure. In: Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2011, vol. 7983. International Society for Optics and Photonics, p. 79830A. https://doi.org/10.1117/12.880156.
Manickam, Ramachandran, prince raja, Bino, D., Jones, Retnam, Stanly, 2015. Analysis of mechanical properties of glass and carbon fiber reinforced polymer material. Int. J. Appl. Eng. Res. ISSN 0973-4562. 10. 10387.
Micelli, F., Nanni, A., 2004. Durability of FRP rods for concrete structures. Construct. Build. Mater. 18 (7), 491–503. https://doi.org/10.1016/j.conbuildmat.2004.04.012.
Nanni, A., 1995. Concrete repair with externally bonded FRP reinforcement. Concr. Int. 17 (6), 22–26.
Padan, E., Bibi, E., Ito, M., Krulwich, T.A., 2005. Alkaline pH homeostasis in bacteria: new insights. Biochim. Biophys. Acta Biomembr. 1717 (2), 67–88. https://doi.org/10.1016/j.bbamem.2005.09.010.
Park, Y., 2012. Long-Term Performance of GFRP Reinforced Concrete Beams and Bars Subjected to Aggressive Environments. Ph.D. Dissertation. The University of Texas. At Arlington. URI: http://hdl.handle.net/10106/11079.
Presuel-Moreno, F.J., Bencosme, R., Hoque, K., Nazim, M., Kazemi, A., Tang, F., 2018. Corrosion Propagation of Carbon Steel Rebars in High Performance Concrete. Florida Atlantic University, Dania Beach and Florida Department of Transportation. Research Report.
Rossini, M., Cadenazzi, T., Nolan, S., Nanni, A., 2018. June). SEACON and resilient FRP-RC/PC solutions: the Halls River Bridge. In: Conference on Italian Concrete Days. Springer, Cham, pp. 165–180. https://doi.org/10.1007/978-3-030-23748-6_13.
Rossini, M., Saqan, E., Nanni, A., 2019. Prediction of the creep rupture strength of GFRP bars. Construct. Build. Mater. 227, 116620. https://doi.org/10.1016/j.conbuildmat.2019.08.001.
Saleh, Z., Goldston, M., Remennikov, A.M., Sheikh, M.N., 2019. Flexural design of GFRP bar reinforced concrete beams: an appraisal of code recommendations. Journal of Building Engineering 25, 100794. https://doi.org/10.1016/j.jobe.2019.100794.
Silica Fume Association, 2017. Life-365 v.2.2.3 [computer software]. Retrieved from: http://www.life-365.org.
Sokri, 2015. Discounting for civilian and military projects. GAU Journal of Social and Applied Science 7 (2), 11–15. ISSNs: 1305–9130.
Tanaka, Y., Kawano, H., Watanabe, H., Nakajo, T., 2006. Study on cover depth for prestressed concrete bridges in airborne-chloride environments. PCI J. 51 (2), 42. https://doi.org/10.15554/pcij.03012006.42.53.
Val, D.V., Trapper, P.A., 2008. Probabilistic evaluation of initiation time of chloride-induced corrosion. Reliab. Eng. Syst. Saf. 93 (3), 364–372. https://doi.org/10.1016/j.ress.2006.12.010.
Wang, H., Belarbi, A., 2013. Flexural durability of FRP bars embedded in fiber-reinforced-concrete. Construct. Build. Mater. 44, 541–550. https://doi.org/10.1016/j.conbuildmat.2013.02.065.
Wei, W., Weichen, X., 2011, April. Advances in durability of FRP bars under alkaline environment. In: 2011 International Conference on Electric Technology and Civil Engineering (ICETCE). IEEE, pp. 1915–1918. https://doi.org/10.1109/ICETCE.2011.5775346.
Xiao, J., Qiang, C., Nanni, A., Zhang, K., 2017. Use of sea-sand and seawater in concrete construction: current status and future opportunities. Construct. Build. Mater. 155, 1101–1111. https://doi.org/10.1016/j.conbuildmat.2017.08.130.
Xie, H.B., Wu, W.J., Wang, Y.F., 2018. Life-time reliability based optimization of bridge maintenance strategy considering LCA and LCC. J. Clean. Prod. 176, 36–45. https://doi.org/10.1016/j.jclepro.2017.12.123.
Younis, A., Ebead, U., Judd, S., 2018. Life cycle cost analysis of structural concrete using seawater, recycled concrete aggregate, and GFRP reinforcement. Construct. Build. Mater. 175, 152–160. https://doi.org/10.1016/j.conbuildmat.2018.04.183.
Zhang, J., Wang, J., Kong, D., 2010. Chloride diffusivity analysis of existing concrete based on Fick's second law. J. Wuhan Univ. Technol.-Materials Sci. Ed. 25 (1), 142–146. https://doi.org/10.1007/s11595-010-1142-4.