ERA-NET Plus on Infrastructure Innovation

SEACON

Sustainable concrete using seawater, salt-contaminated aggregates, and non-corrosive reinforcement

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Report on LCC

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Abbreviations and acronyms

AS Annual Saving
CFRP Carbon Fiber-Reinforced Polymer
CS Carbon Steel
EAC Equivalent Annual Cost
EPD Environment Product Declaration
FDOT Florida Department of Transportation
FRP Fiber-Reinforced Polymer
GFRP Glass Fiber Reinforced Polymer
HCB Hillman Composite Beams
HRB Halls River Bridge
LCC Life Cycle Costing
LCA Life Cycle Assessment
LCI Life Cycle Inventory
LCIA Life Cycle Impact Assessment
NPC Net Present Cost
NS Net Saving
PC Prestressed Concrete
RAP Recycled Asphalt Pavement
RC Reinforced Concrete
RR Reinforcing Ratio
SS Stainless Steel

1 Introduction

WP5 is to ensure and prove that new SEACON-technology is sustainable and beneficial in all its aspects. The objectives of this WP are to analyze and advise the design of developed innovative technologies through LCA (Deliverable 5.3) and LCC aiming at contributing to materials and processes selection and design within environmental and economic criteria.

In the present report, the adoption of innovative reinforced concrete mixes was investigated in terms of economic benefits. Both the Italian and the American demo projects were adopted as case studies for the analysis.

2 The Italian Demo project: the culvert

The culvert is used as a demonstrator to show the feasibility of SEACON technology in harsh environmental conditions, due to the presence of chloride contamination caused by the use of de-icing salts in winter.

The use of seawater is combined with two non-corrosive reinforcements (i.e. GFRP and stainless steel) in the structure. At the same time, carbon steel rebars were also present in the structure to better understand the advantages that a non-corrosive reinforcement can offer in terms of durability.

The culvert is a reinforced concrete structure providing drainage of the outflow waters coming from a motorway. The investigated case study was built along the A1 motorway in Pontenure (Piacenza), see Figure 1, in the area owned by Pavimental. The location and the structure type were chosen based on the harsh environmental conditions, created by the outflow waters coming from the motorway to the culvert.

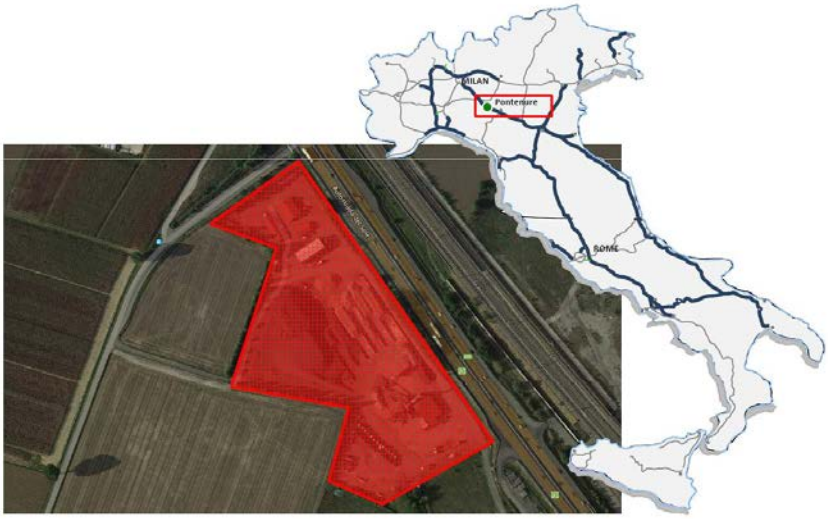

Figure 1 - Territorial framing of the culvert.

The casting of the structure was made in two different phases: firstly, the side walls were cast with reference concrete, the next day, the slab, divided into six segments, was realized using three different concretes, according to the recipes reported in Table 1.

Table 1 - Recipes of the concretes.

Mix design		Reference concrete	SEACON concrete	RAP concrete
CEM II/A-LL 42.5R	kg/m^3	335	335	335
Fly ash	kg/m^3	30	30	30
Sand 0-5 mm	kg/m^3	800	800	766
Gravel 5-7 mm	kg/m^3	365	365	246
Gravel 8-15 mm	kg/m^3	630	630	526
RAP	kg/m^3	-	-	226
Superplasticizer	kg/m^3	2.19	2.19	2.19
Retarding agent	kg/m^3	-	0.76	-
Water	l/m^3	175	-	175
Seawater	l/m^3	-	175	-

The cross-section of the culvert is presented in Figure 2.

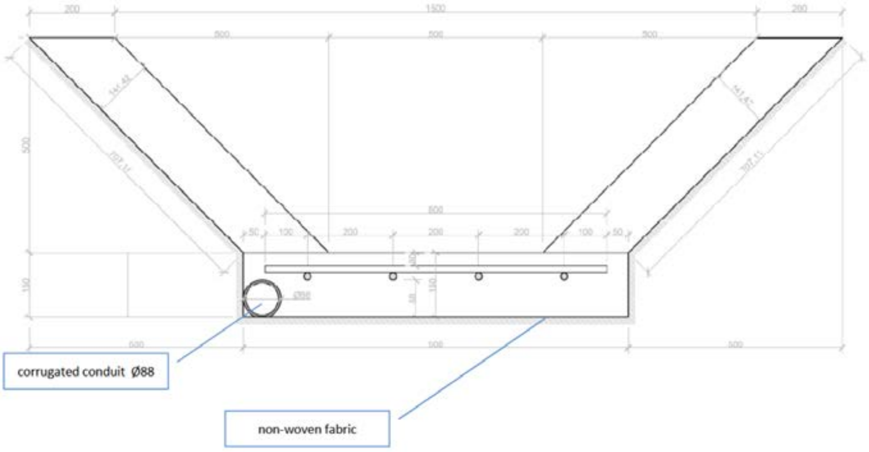

Figure 2 - Culvert cross section.

The culvert is 30 m long and it is divided into 6 segments in which different concretes and reinforcements were used (Figure 3). The six segments were composed of:

- Reference concrete and carbon steel
- SEACON concrete and carbon steel
- SEACON concrete and stainless-steel type 304 (austenitic)
- SEACON concrete and stainless-steel type 23-04 (duplex)
- SEACON concrete and GFRP bars
- RAP concrete and carbon steel

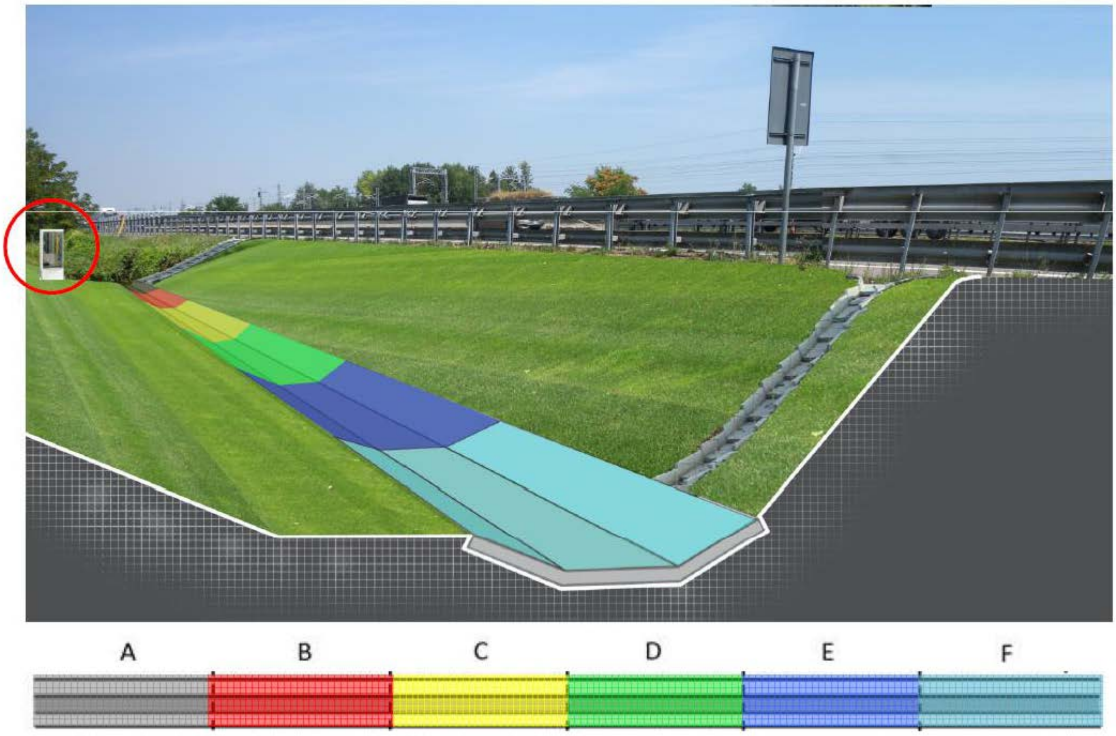

Figure 3 - Scheme of the culvert.

Each section has a volume of 1.675 m^3, divided as 0.675 m^3 slab and 1 m^{3}side walls.
Each slab has a concrete and a reinforcement contents of approximately 0.667 m^3 and 0.0077 m^3 approximately.
The relevant part of the analysis is the slab, where the coupling of specific concrete with different reinforcement was applied. The different types of reinforcement were laid not in contact with each other.
Concrete cover was 30 mm.
Each section was characterized by 4 longitudinal bars 4.8 meters long and 24 transversal bars 0.8 meter long (see Figure 4). Every bar had a constant cross-section of 16 mm. The GFRP reinforcement, due to transportation issues, was realized with two bars 2.7 meters long overlapping for 0.64 meters, resulting in a longitudinal length of 4.8 meters.
A corrugated conduit was realized in order to have space for the electric cables.

Figure 4 - Detail of the reinforcement for a culvert segment.

2.1 Materials

The materials used can be divided in:

- Reinforcement materials
- Components of the concrete mix

The culvert is divided into six sections, and, in each section, a different combination of concrete and reinforcing bar (rebar) was applied. In Table 2, for each section, the combination of rebar material and concrete type is specified.

Table 2 - Summary of reinforcements and concrete (see Figure 3 for the scheme of the culvert).

Segment	A	B	C	D	E	F
Reinforcement	Carbon steel	Carbon steel	SS 304 (1.4311)	SS 23-04 (1.4362)	GFRP	Carbon steel
Concrete	Reference	SEACON	SEACON	SEACON	SEACON	RAP

2.2 LCC methodology

The life cycle cost analysis is a tool to determine the most cost-effective option among different competing alternatives. As for the LCA, the LCC includes all the costs occurring in the life of a product or service.

LCC is particularly suitable for the evaluation of building design alternatives that have different initial investment costs and/or different operating, maintenance, and repair costs. Nevertheless, LCC can be applied to any capital investment decision in which higher initial costs are traded for reduced future costs. LCC provides a significantly better assessment for the long-term cost effectiveness of a project than alternative economic methods that focus only on first costs or on operating-related costs in the short time (Fuller and Petersen, 1996).

The general framework of an LCC is:

- Establish objectives;
- Identify constraints and specify assumptions;

- Define base case and identify alternatives;
- Set analysis period;
- Define level of effort for screening alternatives;
- Estimate benefits and costs relative to base case;
- Compare net benefits and rank alternatives;
- Make recommendations.

An extensive and detailed costs inventory is required for a LCC: the greater the potential savings, the greater the visibility of a project, and the greater the pressure to make a choice based on criteria other than economics, the more important it is to have a thoroughly researched, carefully performed, and well documented study (Fuller and Petersen, 1996).

Another fundamental step of the LCC is the definition of the study period: i.e., the time over which the costs and benefits related to a capital investment decision are of interest to the investor. The same study period must be used in computing the LCC of each project alternative being compared for a given purpose.

2.2.1.1 Environmental Life Cycle Costing

Considering the defined above framework, the LCC is, for certain aspects, similar to the LCA; in this sense, the product life cycle is studied from economic and environmental perspective and the life cycle cost analysis and the life cycle assessment are carried out in parallel obtaining the so-called Environmental Life Cycle Costing.

However, while the LCA usually includes the phases of production, use and consumption, and the end-of-life, the life cycle in LCC may start even earlier since it also may include the “knowledge” phase (e.g., research and development and acquisition via the supply chain) (Hunkeler et al., 2008). Other elements that are usually not included in LCA and are very relevant in the LCC are, for instance, marketing activities, infrastructures, and machineries (Hunkeler et al., 2008).

2.2.1.2 LCC, Net Present Cost (NPC), and discount rate

The following equation (Demos, 2006) is used to calculate the LCC of a product or service:

$$LCC = C_o + \sum_{i=o}^{t} \sum_{j=1}^{n} \frac{C_{i,j}}{(1+r)^i}$$

where:

- C_o represents the initial costs (i.e. all the costs that occur at year zero such as construction costs, material costs, etc.);
- $C_{i,j}$ represents the costs occurring in future, that must be actualized at the year of the analysis (e.g. repairs, etc.);
- t is the time horizon;
- r is the discount rate;
- n is the number of different costs that will occur in future.

The equation is composed of a first term (i.e. initial costs) that is not time dependent and a second term that is time dependent and is called net present cost (NPC). Since most initial expenses occur approximately at the same time, initial expenses are considered to occur during the base year of the study period. Thus, there is no need to calculate the present cost of these initial costs because their present value is equal to their actual cost. The future costs, instead, are time dependent and the present cost equation is used to estimate the future costs at the base year of the study period. The NPC equation is:

$$NPC = \sum_{i=1}^{t} \frac{C_i}{(1+r)^i}$$

NPC takes into account the time-value of the money through the real discount rate (r).

The need to use an economic parameter is due to two main reasons:

- Inflation: inflation is a sustained increase in the general price level of goods and services in an economy over a period of time. When the price level rises, each unit of currency buys fewer goods and services and, consequently, inflation reflects a reduction in the purchasing power per unit of money. Expenditures typically occur at various points in the past or future and are therefore measured in different value units because of changes in price (Demos, 2006).
- Discounting: costs or benefits that occur at different moments in time past, present, and future cannot be compared without allowing for the opportunity value of time. The opportunity value of time considers the economic return that could be earned on funds in their next best alternative use (e.g., the funds could be earning interest). Adjusting for the opportunity value of time is known as discounting (Demos, 2006).

Analytically, adjusting for inflation and discounting are entirely separate concerns, and they should not be confused. Future costs and benefits of a project should be expressed in constant value (or other currency) and then discounted to the present at a discount rate that reflects only the opportunity value of time (known as a real discount rate) (Demos, 2006).

The real discount rate can be calculated as:

$$i = i_{int} - i_{inf}$$

where:

- i_{int} is the current interest rate
- i_{inf} is the interest rate of inflation.

2.2.2 LCC sensitivity analysis

Because distances of GFRP production plant and of sea from the installation site were very high, transportation costs could highly affect LCC results. For this reason a comparative LCC was performed supposing that transportation distances of seawater was the same of tap water and transportation distance of GFRP was the same of steel.

Furthermore, under the hypothesis of same transportation distances, different scenarios were considered changing the amount of concrete removed and replaced during a repair operation with the goal to investigate the relevance of repair operations.

For each analysis, the effect of real discount rate was investigated.

2.3 The system boundary

LCC from cradle to gate was preliminary performed, and then cradle-to-grave perspective was fully adopted: the system boundary included the entire life-cycle from the raw materials extraction until the end-of-life. Side walls were excluded because were the same for each section, therefore irrelevant for the comparative analysis.

Considered costs were construction costs, material costs, repair costs, and end-of-life costs. Construction costs, defined as all the operational initial costs required to build the structure, include the costs of manpower and the costs of the machinery. Both construction and material costs are initial costs (i.e. the total expense occurring at year zero). In the analysis the construction costs did not contain the material costs.

The repair costs were intended to be only the major repair costs, this because minor repairs, inspections, and standard maintenance operations were supposed to be the same for all the design alternatives (Mistry et al., 2016).
At the end of the life (i.e. 100 years) the section was demolished and the materials were transported to landfilling site. Metal scraps, instead, was supposed to be completely resold.

2.4 Costs inventory

Only the costs related to the concrete materials and to the cement mixer were primary and they were furnished directly by Buzzi Unicem. The unitary costs were mainly taken from the price list of Regione Lombardia. Metal scrap values were taken from the Capital Metal Scrap LLC, instead, other values were taken from a study of the Italian Ministry of Infrastructure and Transport.
Costs of the two type of stainless steel (i.e. SS 23-04 and SS 304) were not available, therefore they were supposed the same and equal to the cost of a non-specified stainless steel. Cost of GFRP rebars (16 mm diameter) was directly procured by ATP.
Costs of metal scraps and reinforcements were available in \$/kg, therefore were converted in €/kg using a conversion factor of approximately 1.16 €/\$. Because these values were taken from foreign databases they were not so representative of Italian market.
An indicative selling price of concrete was 135 €/m^3 and was directly indicated by Buzzi Unicem. This was used to derive the cost of mixing and the business profit which were added at the total cost of concrete components (e.g. aggregates, cement, etc.). This was estimated approximately as 108 €/m^3.
Construction costs with GFRP bars were supposed to be the 80% of the constructions costs with steel, this due to the lower weight that eases transportations and placements (Brown, 2015).
Construction costs with steel bars were the same for each section.
Transports of materials were supposed to be executed by lorries (maximum capacity 10 t). For each material was supposed that lorry had transported 60% of the maximum capacity (6 t of material transported) obtaining the unitary cost of transport per kg of material for each specific travel (both going and return were considered). For GFRP transportation, due to the high distance between production plant and installation site, a stop of 45 minutes was considered for both going and return.
For instance:

$$\left(2\,h \cdot 81.41\ {}^{€}\!/_{h} \cdot 2\right)\Big/_{6000\ kg} = 0.05\ {}^{€}\!/_{kg\ of\ steel}$$

$$\left[\left((7\,h - 0.75\,h) \cdot 81.41\ {}^{€}\!/_{h} + 0.75\,h \cdot 49.95\ {}^{€}\!/_{h}\right) \cdot 2\right]\Big/_{6000\ kg} = 0.18\ {}^{€}\!/_{kg\ of\ GFRP}$$

2.5 LCC results from cradle to gate

The results presented in this section considered only the initial costs (i.e. construction costs and material costs) and did not include the operational costs. From cradle to gate using carbon steel bars proved to be the cheapest option (Figure 5).

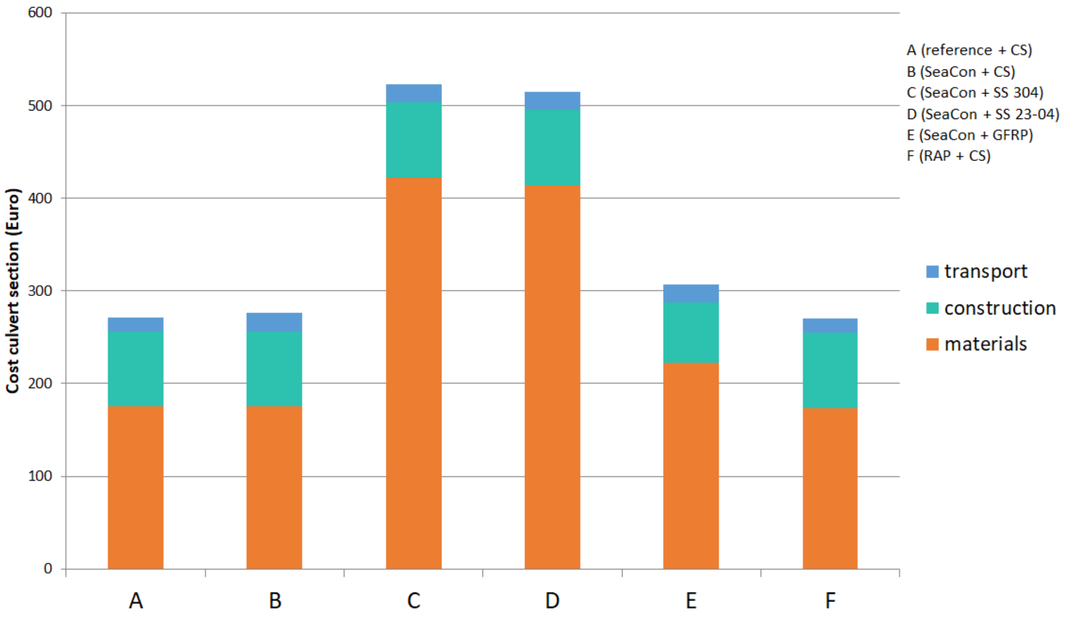

Figure 5 - Costs of the culvert segment from cradle to gate for the base case.

Costs of materials were much larger if compared to construction costs for section E and, in particular, for sections C and D. This difference decreases for the sections A, B, and F due to the use of carbon steel.

2.6 LCC results from cradle to grave for the base case

LCC cradle to grave was performed on the real culvert structure. The effective transportation distances and relative costs were considered.

The structure was supposed to be demolished at the end of the study period, materials without values landfilled and metal scrap sold.

GFRP scraps were supposed to be without residual value due to the complex, heterogeneous, and anisotropic characteristics that make it difficult to be reused or recycled (Yazdanbakhsh and Bank, 2014). This assumption may not be true in 100 years.

The expenses of a single repair operation was equal to 350 €/m^2, 50% of the materials were supposed to be removed from 10% of the exposed surface (Mistry et al., 2016). ACI LIFE365 software, suggests as default value for repairing operations 400 \$/m^2, which correspond to approximately to 340 €/m^2. The value is very similar to the one used in this study. The maintenance schedule is specified in Table 3.

Table 3 - Maintenance schedule.

	A	C	D	E	F
20 years	Repair	/	/	/	Repair
40 years	Repair	/	/	/	Repair
60 years	Repair	/	/	/	Repair
80 years	Repair	/	/	/	Repair
100 years	End-of-life	End-of-life	End-of-life	End-of-life	End-of-life

Real discount rate was fixed at 0.01% as indicated by the SETAC (Society of Environmental Toxicology and Chemistry) for long-term investments. A sensitivity analysis was also performed to show the relevance of the real discount rate on the discounting of future activities.

The result of LCC for base case is presented in Figure 6. Given that only 5% of the cover was affected by the repair, the cost of a single repair operation was quite low. Therefore, total maintenance costs detemined higher costs for section A and F, this due to the manpower and materials employed in repair operations.

End-of-life was quite similar for each segment, but for sections C and D has the lowest cost thanks to the higher value of stainless steel scraps that were resold. The value of carbon steel scraps was low compared to stainless steel scraps, therefore the end-of-life phase was more expensive with respect to sections C and D.

With a real discount rate of 0.01% section A and F were the worst, and stainless steel results to be a prefarable choice to carbon steel. The use of GFRP bars, thanks to the low weight, reduced the manpower cost at construction site. Moreover, the relatively low cost of the material and the absence of major repairs made section E the most cost saving option (Figure 6).

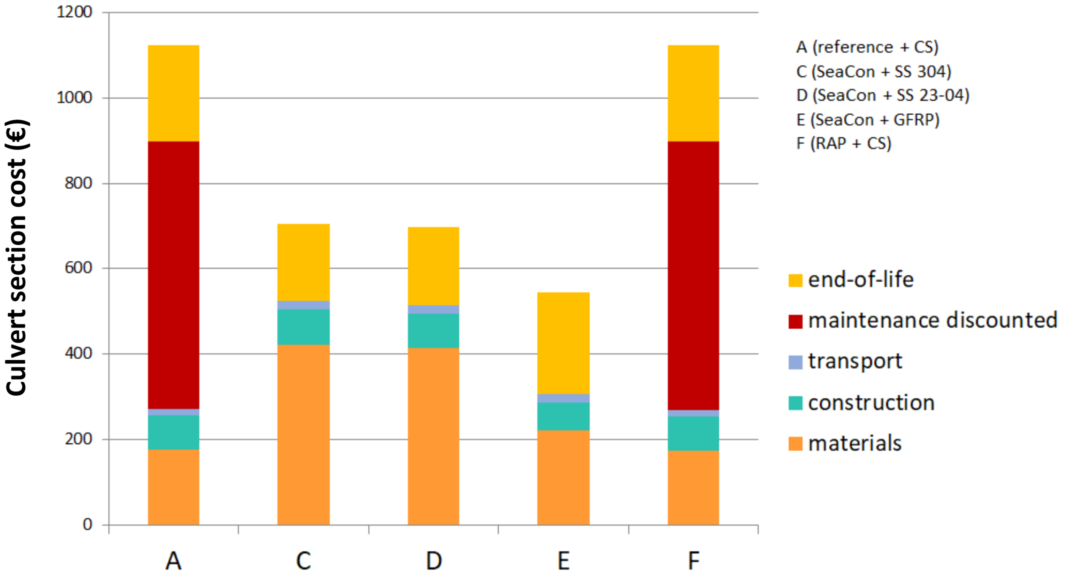

Figure 6 - LCA results from cradle to grave for the base case.

A sensitivity analysis was performed to understand the relevance of the real discount rate on the analysis results. Increasing the real discount rate, total repair costs tend to decrease due to the inverse proportionality in the NPC relation. The high initial costs of high-durability rebars may not be recovered during the life of the structure.

The real discount rate for which the use of stainless steel reinforcements becomes unfavorable with respect to carbon steel was approximately 1%. On the other hand, GFRP bars remained the best reinforcing option up to a real discount rate of approximately 5%.

2.7 Sensitivity analysis

Two scenarios were considered for the operational stage of the culvert:

- 1A) Repair operations were performed on the 10% of the exposed surface and 100% of the materials were substituted, in accordance with ACI LIFE365 software. The same costs and maintenance schedule used in scenario 1 were adopted.
- 2A) The maintenance schedule was changed: the first repair operation was considered to be performed at the end of the service life (i.e. 20 years for section A and F) and, after that, a repair was executed every ten years. The choice was in agreement with the ACI LIFE365

software. Repair operations were supposed to be executed on 50% of the total exposed surface and it consisted in the removal of the concrete cover, the removal of the rust on the bar, and the reconstruction of the cover with fiber reinforced thixotropic cement mortar. Costs were taken from the price list of Regione Lombardia (Lombardia, 2011). Prices in the list were inclusive of manpower, transportations, and material costs. Metal scraps value was the same of the other scenario. Cost of GFRP was the sum of material cost and the manpower for placement, which corresponded to 80% of the manpower for steel placement.

A third scenario (3B) was considered using the hypothesis of scenario 2B, but it was supposed that reinforcing ratio of GFRP was twice RR of steel and repair operation was executed on 50% of exposed surface.

In all cases, at the end of the study period (i.e. 100 years), the structure was supposed to be demolished, materials without values landfilled and metal scrap sold. Furthermore, the real discount rate was fixed at 0.01%. A sensitivity analysis was also performed to show the relevance of the real discount rate on the discounting of future activities.

Transportation distances were considered the same for each section; therefore transportation costs were negligible for the comparative analysis.

2.7.1 Results (Scenario 1B)

The result of this scenario is presented in Figure 7. The cost of a single repair operation increased since 10% of the cover was recovered. Due to this increment, the relevance of the maintenance appeared evident and both GFRP bars and stainless steel bars resulting very interesting cost saving options. In particular, the total cost for section E (SeaCon + GFRP) was approximately half the cost for section A (Figure 7).

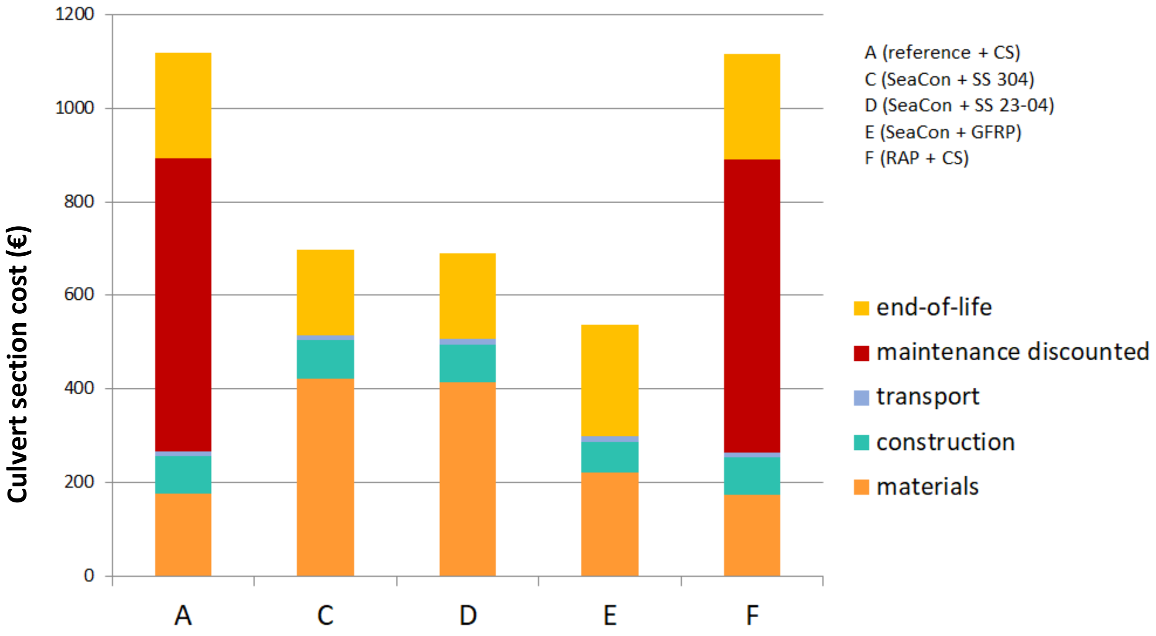

Figure 7 - LCC results for scenario 1B (10% of concrete cover replaced)

A sensitivity analysis varying the real discount rate was performed for this scenario as well. Section C and D proved to be cheaper than section A until the real discount rate was approximately 2.6%; conversely, section E was the best choice until a real discount rate of approximately 7.6% was adopted.

2.7.2 Results (Scenario 2B)

In scenario 2B, the cost of a repair operation decreased but repair operations were executed on the 50% of the entire concrete cover and, therefore, the cost of a single repair operation increased. The results of the LCC analysis for scenario 2B are presented in Figure 8. With this hypothesis and considering the previous results (base case and Scenario 1) with a real discount rate of 0.01%, the choice of high durability reinforcements was very favorable.
Life cycle costs for section A were approximately 4 times higher than the costs for section C (or D) and they were approximately 5 times higher than the costs for section E (Figure 8).

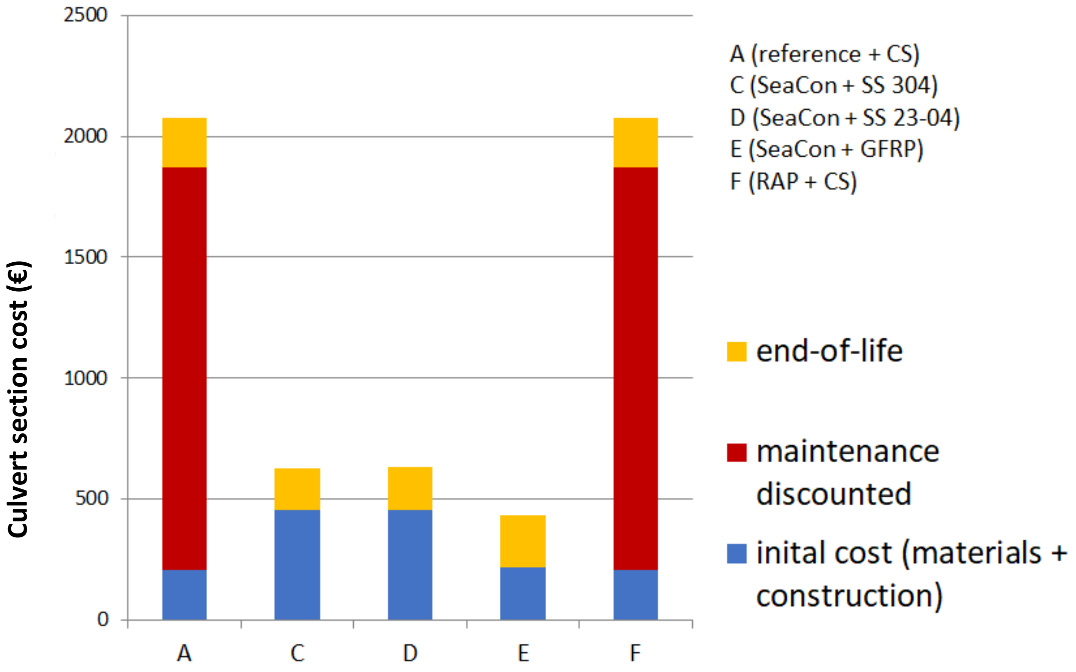

Figure 8 - LCC results for scenario 2B.

The sensitivity analysis showed that the use of stainless steel reinforcement is preferable to carbon steel until the real discount rate was approximately 5%, instead; on the other hand, the use of GFRP bars was the cost saving cheaper until the real discount rate was approximately 14%.

2.7.3 Results (Scenario 3B)

The result of scenario 3B is presented in Figure 9. Despite the twice in amount of GFRP in section E with respect to the base case, section E showed the lowest costs. This was determined by the low weight of GFRP that was approximately 1/4 of steel weight.

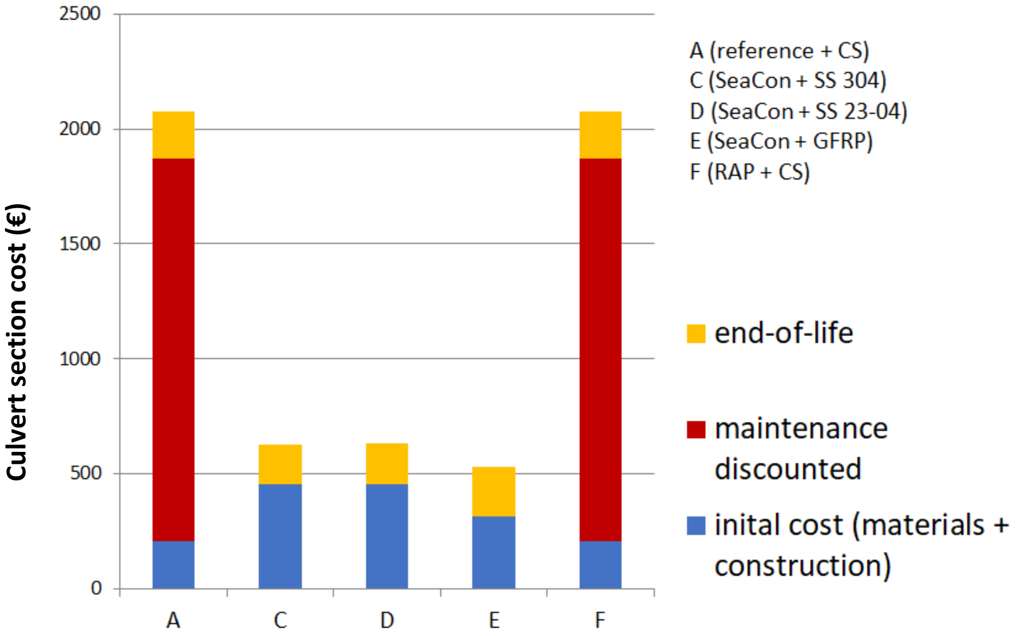

Figure 9 - LCC results for scenario 3 (doubling the amount of GFRP in section E).

2.8 Conclusions

A reinforced concrete structure was studied with the aim to understand if alternative concrete mix designs combined with high-durability reinforcements could decrease costs associated to the entire life of the structure. The method used in the present study to analyze the possible economic benefits associated to the use of non-conventional materials was the Life Cycle Costing (LCC).

Several reinforcing materials were considered: carbon steel (CS), stainless steel (SS), and Glass Fiber Reinforced Polymer (GFRP). The rebars were combined with non-conventional concrete mixes, in particular SEACON and RAP (a concrete with a partial replacement of natural aggregates with Recycled Asphalt Pavement aggregates).

The case study was a culvert placed in Pontenure (Piacenza, Italy) composed of six sections:

- Section A: CS + reference concrete;
- Section B: CS + SEACON concrete;
- Section C: SS 304 + SEACON concrete;
- Section D: SS 23-04 + SEACON concrete;
- Section E: GFRP + SEACON concrete;
- Section F: CS + RAP.

Each section was studied using LCC. Different scenarios were considered to understand the relevance of input parameters and maintenance schedule on LCC results.

In the following some considerations can be carried out:

- The use of recycled aggregates resulted in an extremely small cost saving.
- Sections containing stainless steel bars were characterized by the highest initial costs but did not require any major repair operation.
- Stainless steel proved to be a cost saving option with respect to carbon steel bars when either the real discount rate was very low (lower than 1% supposing that one repair operation affected 5% of the concrete cover) or the repairing costs were consistent. To conclude, stainless steel bars proved to have a lower cost with respect to carbon steel rebars under the assumption considered (i.e. real discount rate of 0.01%).

- The use of GFRP had the highest economic performance mainly due to the low weight that reduces the mass of the rebars (lower consumption of raw materials), the transport costs and the manpower. The only drawback of this material seems to be the current impossibility of recycling it at the end-of-life. From a circular economy point of view, it means that all the reinforcing material would go to landfill at the end-of-life, in opposition to steel which can be completely recycled.

Several sensitivity analyses were performed to show the relevance of key parameters: number and cost of repair operations, reinforcing ratio of GFRP, and real discount rate.

Repair operations highly affected LCC results determining that high-durability rebars are preferred in aggressive environments for long time horizons (i.e. 100 years in the present study).

Real discount rate has a high influence on discounted maintenance costs. For the base case (i.e. repair cost 350 €/m^2 with 5% of the concrete cover replaced) stainless steel rebars and GFRP rebars resulted economic favorable with respect to carbon steel until the real discount rate was approximately 1% and 5% respectively.

LCC showed that GFRP reinforcement remained the cheapest solution even doubling the amount of GFRP rebars and maintaining fixed the amount of steel reinforcements. Furthermore, same reinforcing volume, GFRP proved to be the reinforcing material with highest economic performance.

3 The American Demo project: the Halls River bridge (Cadenazzi; et al., 2018)

This research pertains the life-cycle-cost (LCC) estimation of a FRP-RC/PC short-spanned traffic bridge. The specific structure considered, named the Halls River Bridge (HRB), is currently under construction in Homosassa, Florida. The structure serves as demonstrator for the international SEACON research project. The effort is aimed to develop sustainable concrete using seawater, salt-contaminated aggregates, and non-corrosive reinforcement (Bertola et al., 2017).

The approach detailed in this study can serve as a guideline for further implementation of LCC techniques to FRP-RC/PC infrastructures. The cost of the FRP-RC/PC solution will be compared to a traditional steel-RC/PC alternative. The steel-RC/PC solution is designed for a 75-year service life (AASHTO, 2014). Conversely, the FRP-RC/PC alternative is designed for a 100-year service life without major maintenance, in line with current state-of-the-practice (Fib, 2007). The cost comparison is performed at the construction phase. Maintenance and repair costs for the steel-RC/PC alternative are not included at this stage and are expected to add to the economic appeal of FRP reinforcement over the long term (Haghani and Yang, 2016).

The structure considered is a short-spanned traffic bridge. It pertains five spans for a total length of 56.60 m, with 3.66 m wide traffic lanes and sidewalks on both sides. The structure consists of 36 CFRP-PC 460 mm by 460 mm bearing piles, 149 CFRP-PC/GFRP-RC 300 mm x 760 mm sheet piles, 6 GFRP-RC bent caps, 86 Hybrid TCS-PC/GFRP-RC 300 mm x 760 mm sheet piles, 45 GFRP-RC girders, 6 GFRP-RC bent caps, GFRP-RC bulkhead caps, innovative traffic railings, and approach slabs and a 20m long GFRP-RC gravity wall. The original design implemented Hillman Composite Beams (HCB), consisting of a composite shell over a steel-reinforced concrete core. In this report a consistent fully FRP-RC/PC design alternative is considered. HCB are replaced with a GFRP-RC alternative that provides equivalent strength and performance. Figure 10 shows the plan and elevation view of the entire bridge.

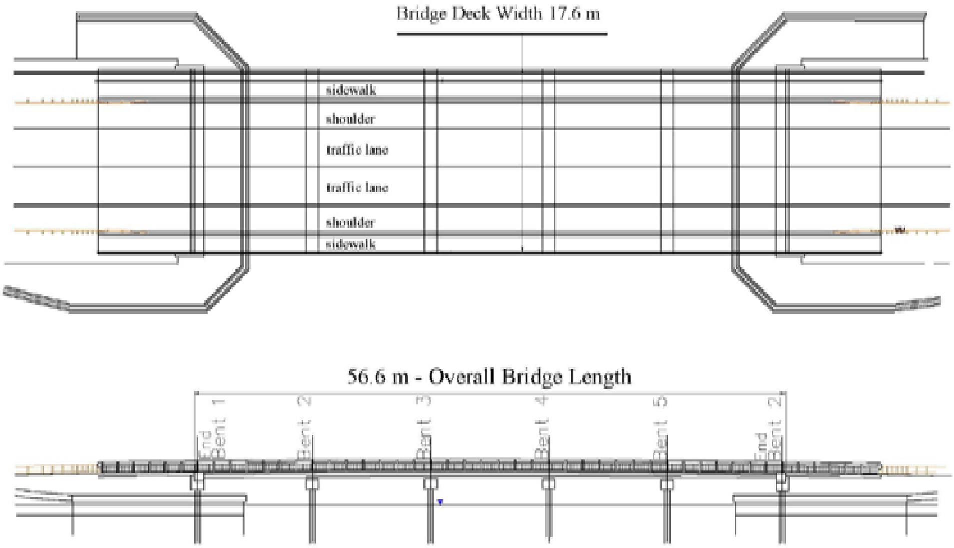

Figure 10 - Plan and elevation view of the proposed FRP-RC Bridge.

3.1 Life-Cycle Cost Analysis

The analysis is performed in compliance with the international standard ISO 15686-5, 2008. According to ISO 15686-5, 2008 the costs that should be included in LCC analysis are those relative to the construction, operation, maintenance, and end-of-life. Generally, maintenance includes replacement or repair.

Figure 11 shows different life-cycle phases of a project, as detailed by Haghani (Haghani and Yang, 2016) and ISO 15686-5, 2008. The three final phases, from the beginning of construction to the end of life, are the phases of main interest, in which the construction of assets takes place.

Figure 11 - Whole-life cost classification.

Figure 12 shows a classification of all the cost considered in a life-cycle analysis. Costs are categorized into direct costs and indirect costs (Haghani and Yang, 2016). Direct costs are defined as the costs faced by the owner during design, construction, and maintenance, until the end of life. Indirect costs are subdivided into user and society costs

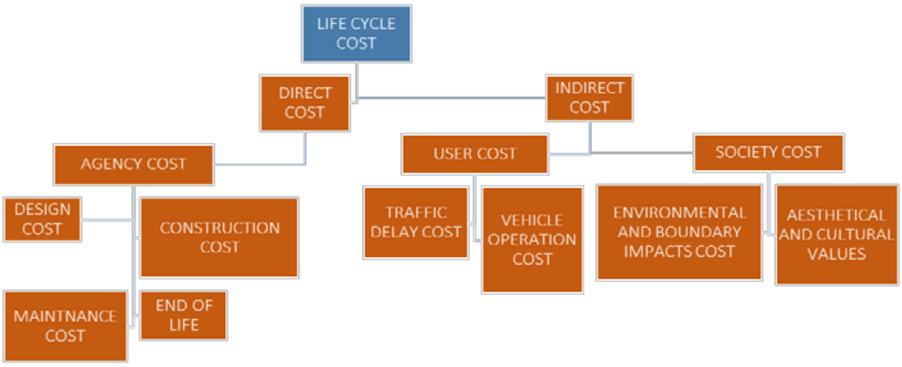

Figure 12 - Classification of costs.

In this study, the focus is on Agency costs at construction phase and Users costs. The maintenance component is expected to be more relevant on the steel side (Haghani and Yang, 2016) and would add to the economic appeal of the FRP-RC/PC alternative. The total cost presented in this paper includes all the activities necessary to complete the bridge, even though not all of them are detailed in this study because not involving directly FRPs. GFRP-RC traffic railings and gravity wall construction is also not detailed because of its minor impact.

3.2 Transportation and testing cost

Transportation cost depends on the weight of the material. Table 4 compares the quantity of cast in-place reinforcement needed for the project to an equivalent steel alternative. The same amount of reinforcement is considered in the two cases, a more refined approach requires to consider the different mechanical properties of GFRP and CFRP with respect to steel reinforcement. The reduced stiffness of composite bars may require a larger amount to be considered to satisfy serviceability limit state design.

Table 4 includes the reinforcement required for the deck, bulkhead caps, bent caps, gravity walls, approach slabs and traffic railings, estimated in a total of 31,556 kg of GFRP reinforcement. The same amount of steel reinforcement weights 124,990 kg.

Table 4 - GFRP reinforcement for cast-in place elements.

Alternative	Item	Alternative	Unit weight [kg/m]	Unit weight [lbs/lf]	Quantity	UM	Tot. Weight [kg]	Project load [kg]
GFRP	Bars #3	GFRP	0.19	0.13	222	m	42	**31,556**
	Bars #4	GFRP	0.29	0.19	7,142	m	2,071	
	Bars #5	GFRP	0.39	0.26	24,266	m	9,464	
	Bars #6	GFRP	0.56	0.38	26,360	m	14,762	
	Bars #8	GFRP	0.98	0.66	5,324	m	5,217	
STEEL	Bars #3	Steel	0.56	0.38	222	m	125	**124,990**
	Bars #4	Steel	0.99	0.67	7,142	m	7,070	
	Bars #5	Steel	1.55	1.04	24,266	m	37,612	
	Bars #6	Steel	2.24	1.5	26,360	m	59,047	
	Bars #8	Steel	3.97	2.67	5,324	m	21,136	

The implications of FRP light weight on the transportation costs are significant. The use of a GFRP-RC cast-in-place design cut transportation costs of reinforcement to the construction site to ¼ with respect to a steel-RC solution.

While a significant saving is experienced on the transportation side, the use of FRP reinforcement introduces testing costs not experienced with steel reinforcement (Ehlen, 1999). The Florida Department of Transportation (FDOT) requires each lot of FRP reinforcement to undergo specific testing before deployment (FDOT, 2016). Required tests are specified in Table 5 and shall be performed by a certified laboratory.

Table 5 - Additional test required for FRP.

Standard Test Method	Test Description	Acceptance Criteria #4	#5	#6	#8
ASTM E2160	Degree of cure	>95%	>95%	>95%	>95%
ASTM D2584	Fiber Content	>70%	>70%	>70%	>70%
ASTM D570	Moisture Absorption short term	≤ 0.25%	≤ 0.25%	≤ 0.25%	≤ 0.25%
ASTM D792	Measured Cross Sectional Area	126.45 mm^2 ≤ x ≤ 150.97 mm^2	198.06 mm^2 ≤ x ≤ 236.77 mm^2	285.16 mm^2 ≤ x ≤ 341.29 mm^2	506.45 mm^2 ≤ x ≤ 607.74 mm^2
ASTM D7205	Ultimate Tensile Strength	758.42 MPa	655.00 MPa	637.77 MPa	586.05 MPa
ASTM D7205	Tensile Modulus of Elasticity	≥ 44,816 MPa	≥ 44,816 MPa	≥ 44,816 MPa	≥ 44,816 MPa

Overall, the cost of the tests if set to $ 16,060, assuming the bars to be shipped in a single lot.
The expectation is that testing requirements will be progressively relaxed and eventually lifted as the material gets widely accepted. This will result in positive economic implications for the owners, as well as easing construction and deployment.

3.3 Agency cost

This section focuses on the items where FRP implications are critical, at the construction stage. Remaining components are included, but not detailed in this study. In particular, the initial cost of materials, fabrication process, transportation, construction and installation cost are taken into account. The cost components are design-based and defined as a function of the initial project schedule. All construction-related activities are scheduled to last 310 calendar days. Table 6, Table 7, Table 8, Table 9, and Table 10 show costs in terms of material, labor and equipment required to perform the activities. Hourly equipment costs are calculated as the sum of idle and operating cost. The idle component is equal to the total ownership cost divided by 176 (22 working days multiplied by 8 working hours per day), while the operating component includes fuel and maintenance of the machine.
Table 6 shows the installation costs for the substructure. The substructure consists of the CFRP pre-stressed piles and bent caps. The total cost of substructure works is estimated in $ 711,142 over a duration of 51 days.
Table 7 shows the installation costs for the CFRP-PC/GFRP-RC sheet piles. The total cost of sheet pile works is estimated in $ 1,330,926 over a duration of 37 days.
Table 8 shows the installation costs for the bulkhead cap. The total cost of bulkhead cap works is estimated in $ 64,619. Given the large scale of the elements, the reinforcement cost does not have a significant effect on the grand total, while a cost saving is expected for all the cast-in place members, thanks to the lightweight of the material. The lightweight reduces equipment costs, as well as fuel consumptions. It also partially reduces on-site labor and construction time, allowing for a more aggressive schedule. Construction time is a critical factor, as it affects not only production costs, but also the user cost. User cost is defined as a monetary measure of delays experienced by automobile drivers on the road.

Table 6 - Piles and bent caps activity.

Piles and bent caps – duration 51 days		Quantity		UM		Unit Cost	Total Cost
Material	CFRP- Pre-stressed RC piles 18'' square	576		m		$ 468.63	$ 269,825
	Accessories for concrete piling	576		m		$ 32.81	$ 18,890
	GFRP #4	119		m		$ 2.36	$ 280
	GFRP #5	6,871		m		$ 3.81	$ 26,151
	GFRP #6	244		m		$ 4.99	$ 1,216
	GFRP #8	3,155		m		$ 8.56	$ 27,019
	Formwork	139		m^3		$ 52.32	$ 7,292
	Accessories for concrete works	139		m^3		$ 39.24	$ 5,469
	Concrete Class IV	137		m^3		$ 160.25	$ 21,998
	Neoprene pads	0.5		m^3		$ 24,500	$ 12,250
Labor		Quantity		Hrs		Unit Cost	Total Cost
	Crane Operator	2		408		$ 44.27	$ 36,124
	Skilled Laborer	2		408		$ 15.22	$ 12,420
	Pile Driver	4		208		$ 27.67	$ 23,021
	Carpenters	6		72		$ 29.50	$ 12,239
	Foreman	2		408		$ 46.69	$ 38,099
Equipment		No.	Oper Hrs	Idle Hrs	Oper Cost	Idle Cost	Total Cost
	Crawler Crane 230 TON	2	408	0	$ 126.75	-	$ 103,428
	Hydraulic Impact Hammer	2	104	104	$ 173.72	$ 52.27	$ 47,006
	Air Compressor 185 CFM	1	125	83	$ 11.95	$ 2.70	$ 1,718
	Auger Drill 22''	1	104	104	$ 86.55	$ 51.48	$ 14,355
	Heavy Centrifugal Pump	1	166	42	$ 20.02	$ 14.72	$ 3,942
	Concrete Pump Trailer mounted	1	42	366	$ 35.57	$ 16.67	$ 7,595
	Mobile Crane	1	103	125	$ 146.85	$ 45.45	$ 20,807
Grand Total							**$ 711,142**

Table 7 - Sheet piles activity.

Sheet Piles – duration 37 days		Quantity [m]				Unit Cost	Total Cost
Material	CFRP-RC sheet piles	1905				$ 524.02	$ 998,410
	Accessories for concrete sheet piling	1905				$ 32.81	$ 62,510
Labor		Quantity		Hrs		Unit Cost	Total Cost
	Crane Operator	2		296		$ 44.27	$ 26,208
	Skilled Laborer	4		296		$ 15.22	$ 18,020
	Pile Driver	2		296		$ 27.67	$ 16,381
	Foreman	2		296		$ 46.69	$ 27,640
Equipment		No.	Oper	Idle Hrs	Oper Cost	Idle Cost	Total Cost
	Crawler Crane 230 TON	2	296	0	$ 126.75	-	$ 75,036
	Vibratory Hammer	2	148	148	$ 116.86	$ 42.61	$ 47,203
	Air Compressor 185 CFM	1	178	118	$ 11.95	$ 2.70	$ 2,446
	Auger Drill 22''	1	148	148	$ 86.55	$ 51.48	$ 20,428
	Heavy Centrifugal Pump	2	237	59	$ 20.02	$ 14.72	$ 11,226
	Mobile Crane	1	118	178	$ 146.85	$ 45.45	$ 25,418
Grand Total							**$ 1,330,926**

Table 8 - Bulkhead cap installation.

Bulkhead Cap– duration 5 days		Quantity		UM		Unit Cost	Total Cost
Material	Concrete Class IV	73		m^3		$ 160.3	$ 11,647
	Bridge Deck Expansion Joint	35		m		$ 192.6	$ 6,810
	GFRP #5	3,517		m		$ 3.8	$ 13,386
	GFRP #6	223		m		$ 5.0	$ 1,113
	Formwork	69		m^3		$ 39.2	$ 2,715
	Accessories for concrete works	69		m^3		$ 52.3	$ 3,620
Labor		Quantity		Hrs		Unit Cost	Total Cost
	Crane Operator	2		40		$ 44.3	$ 3,542
	Skilled Laborer	1		40		$ 16.2	$ 649
	Carpenters	2		40		$ 28.3	$ 2,266
	GFRP Fixer	2		40		$ 29.5	$ 2,360
	Foreman	2		40		$ 46.7	$ 3,735
Equipment		No.	Oper Hrs	Idle Hrs	Oper Cost	Idle Cost	Total Cost
	Crawler Crane 230 TON	2	32	8	$ 126.7	-	$ 8,112
	Concrete Pump Trailer mounted	1	8	32	$ 35.6	$ 16.7	$ 818
	Mobile Crane	1	20	20	$ 146.9	$ 45.5	$ 3,846
	Grand Total						**$ 64,619**

Table 9 - Girders installation activity.

Girders – duration 6 days			Quantity [m]			Unit Cost	Total Cost
Material	Precast RC GFRP beam		495			$ 432.6	$ 214,130
	Accessories for girders		495			$ 49.2	$ 24,360
Labor		Quantity		Hrs		Unit Cost	Total Cost
	Crane Operator	2		48		$ 44.3	$ 4,250
	Skilled Laborer	2		48		$ 16.2	$ 1,557
	Carpenters	2		48		$ 28.3	$ 2,720
	Truck Driver	1		4		$ 25.0	$ 100
	Foreman	2		48		$ 46.7	$ 4,482
Equipment		No.	Oper Hrs	Idle Hrs	Oper Cost	Idle Cost	Total Cost
	Crawler Crane 230 TON	2	288	0	$ 126.7	-	$ 73,008
	Flatbed Truck	1	4	284	$ 39.4	$ 18.2	$ 5,313
	Grand Total						**$ 329,920**

Table 9 shows the installation cost for the girders. The total cost for girder works is estimated in $ 329,920. For the girders fabrication cost, as well as for piles and sheet piles, the total includes a typical 5-man-crew labor component, while equipment is not directly included. Equipment cost is included in the plant overhead component. Plant overhead is defined independently by each fabricator as a function of sale price, volume of concrete, or cost of direct labor. Overhead typically includes design, quality control, equipment, construction, operating costs (such as electricity, fuel, etc.), insurance, and sales. Also the cost of the mold is considered in the overhead component.
Table 10 shows the installation cost for the deck. The total cost for deck works is $ 454,059.
In all the previous activities, on-site labor costs are considered as a function of production rates and are calculated and weighted to account for project size, materials deployed, and depends on market conditions at the time of construction.

Table 10 - Deck placement activity.

Deck– duration 36 days		Quantity		UM		Unit Cost	Total Cost
Material	Concrete Class IV	258		m³		$ 122.5	$ 41,424
	Bridge Deck Expansion Joint	35		m		$ 58.7	$ 6,810
	GFRP #4	6,865		m		$ 0.7	$ 16,217
	GFRP #5	3,475		m		$ 1.2	$ 13,224
	GFRP #6	25,893		m		$ 1.5	$ 129,127
	GFRP #8	596		m		$ 2.6	$ 5,100
	SIP deck	8092		m²		$ 4.0	$ 38,809
	Formwork	246		m³		$ 30.0	$ 9,660
	Accessories for concrete works	246		m³		$ 40.0	$ 12,880
Labor		Quantity		Hrs		Unit Cost	Total Cost
	Crane Operator	2		288		$ 44.3	$ 25,500
	Skilled Laborer	2		288		$ 16.2	$ 9,343
	Carpenters	2		288		$ 28.3	$ 16,318
	Steel Fixer	1		167		$ 29.5	$ 4,926
	Foreman	2		288		$ 46.7	$ 26,893
Equipment		No.	Oper Hrs	Idle Hrs	Oper Cost	Idle Cost	Total Cost
	Crawler Crane 230 TON	2	288.0	0.0	$ 126.7	-	$ 73,008
	Concrete Pump Trailer mounted	1	57.6	230.4	$ 35.6	$ 16.7	$ 5,889
	Mobile Crane	1	57.6	230.4	$ 146.9	$ 45.5	$ 18,930
			Grand Total				**$ 454,059**

3.4 User cost

The user cost is defined as the indirect cost for any delayed vehicle due to construction. It comprises travel delay cost and vehicle operation cost including fuel, oil, and vehicle maintenance(Haghani and Yang, 2016, Eamon et al., 2012).
During construction, 2-lane traffic is limited to one lane, phased by traffic lights, and assisted by trained flaggers during critical construction activities. The decision to maintain the bridge operational during construction is dictated by the owner. The structure serves the only access-way to the city of Homosassa (FL) from Homosassa Springs (FL).

Equation (1) to (3) allow to compute the user cost as (Haghani and Yang, 2016):

$$C_{user} = C_{TDC} + C_{VOC} \qquad (1)$$

$$C_{TDC} = T \cdot ADT_t \cdot N_t \cdot (r_T w_T + (1 - r_t) \cdot w_p) \qquad (2)$$

$$C_{VOC} = T \cdot ADT_t \cdot N_t \cdot (r_T O_T + (1 - r_t) \cdot O_p) \qquad (3)$$

where: C_{user} is the user cost, C_{TDC} is the travel delay cost, C_{VOC} is the vehicle operation cost, T is the travel time delayed for one vehicle (0.025 hours), ADT_t is the average daily traffic on the bridge (1432 vehicles/day), N_t is the number of days of road work at time t (136 days), r_T is the percentage of trucks among all the ADT_t (10%), w_T is the hourly cost for one truck (7 \$/hour), w_p is the hourly cost for one passenger car (3 \$/hour), O_T is the hourly operation cost for one truck (25 \$/hour), and O_p is the hourly operation cost for one passenger car (10 \$/hour) (Haghani and Yang, 2016).
Thus, the travel delay cost C_{TDC} is computed in \$ 16,553, while the vehicle operation cost C_{VOC} is computed in \$ 55,991. The user cost adds up to \$ 72,545.

3.5 Results

Table 11 presents the construction costs associated to two possible alternatives considered in the design phase. The construction cost for the FRP-RC/PC alternative is estimated in \$ 6,015,645 with a service life projected to 100 years. Conversely, the construction cost for the steel-RC/PC solution is estimated in \$ 5,487,182, with a service life set at 75 years.

Table 11 – Results table.

	Existing Steel Alternative	FRP New Design Alternative
Construction Cost	\$ 5,487,182	\$ 6,015,645
EAC	73,162	\$ 60,156
Service Life (years)	75	100
Net Saving		\$ 318,711

The construction cost of the steel-RC/PC alternative is estimated through Equation (4). Only the difference in material cost is taken into account. The same volume of reinforcement is considered for the two alternatives, whereas a lower amount of steel reinforcement may be required. In addition, this simplified approach does not take into account the increased labor and equipment costs on the steel-RC/PC side. The difference is expected to be significant for cast in-place activities.

$$C_{steel,\,tot} = C_{FRP,\,tot} - C_{FRP,\,materials} + C_{steel,\,materials} \qquad (4)$$

The life cycle cost is expressed in terms of Equivalent Annual Cost (EAC). The alternative with a lower EAC is more cost-efficient. If the more cost-efficient alternative is implemented, the benefit can be computed in terms of annual saving (AS) using Equation 5 (Haghani and Yang, 2016):

$$AS = EAC_{steel} - EAC_{FRP} = \frac{5{,}487{,}182}{75} - \frac{6{,}015{,}645}{100} \qquad (5)$$

where: EAC_{steel} is the equivalent annual cost of the steel-RC/PC alternative, and EAC_{FRP} is the equivalent annual cost of the FRP-RC/PC solution, which is more cost-efficient. Total annual saving are estimated in $ 13,005

The concept of annual saving can be further developed into net saving (NS) (Equation 6) with respect to the life-span of the more cost-efficient alternative (100 years)

$$\mathrm{NS} = \mathrm{AS} \cdot \frac{1-(1+r)^{-L_2}}{r} \tag{6}$$

where r is the discount rate, L_2 is the life span of the FRP-RC/PC alternative, which is more cost-efficient. The discount rate is set to 4 percent per year (Haghani and Yang, 2016). Net saving is thus estimated in $ 318,711.

3.6 Conclusions

In this study, a design-based LCC analysis of a FRP-RC/PC bridge is presented. Among the direct costs, this report focuses on the construction costs of the main FRP structures. Among the indirect costs, this report investigates those correlated to the user costs.

Despite its higher construction cost, FRP-RC/PC is a life-cycle-cost-effective alternative to conventional steel-RC/PC solutions. FRP is durable and light-weighted which allows to project an aggressive construction schedule, reducing not only construction costs but also indirect driver costs caused by bridge works.

In addition, among the indirect cost, the user cost is estimated to show the impact that a replacement construction has on users. It is important to note that the user cost of an FRP-RC/PC solution is less impacting than a steel-RC/PC alternative. This is an additional positive implication of a more aggressive schedule that leads to a faster construction time-frame.

Experience suggests that a steel-RC/PC structure hardly endure its projected service life without undergoing maintenance and reparation to account for loss of strength following corrosion of the reinforcement (Nolan and Nanni, 2017). In this study, repair costs on the steel-RC/PC side were not included in the analysis. An in-depth investigation on the maintenance side is expected to further emphasize the economic appeal of FRP-RC/PC solutions.

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