Lifecycle Assessment of Different Constructive Solutions in Aggressive Maritime Environments - Application to the Viaduct of the Oil Terminal of the Port of Leixões

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Abstract

The maritime environment is one of the most aggressive for infrastructures. This type of exposure affects severely the durability of any infrastructure, if proper preventive measures are not taken into account.

In the construction of new structures one of the most important factors to take into account is the ratio cost / durability. This way, it is intended to make a study of two different structural solutions, as well as an analysis of their life cycles, for the viaduct of the oil tanker terminal of port of Leixões, in Portugal, since the current structure has reached the end of its life cycle after 50 years. It will be then designed a solution of precast and pre-stressed reinforced concrete beams with a reinforced concrete slab, and another solution with steel beams with a reinforced concrete slab. The new structure will be designed according to current regulations, which are developed in a way that such structures should reach a service life of 100 years.

It is expected that this study will be able to provide a solution that is economically viable for the replacement of the viaduct, and where it is possible to reach the expected life time of 100 years with the lowest possible cost.

Keywords: Maritime environment; Viaduct; Life cycle; Durability; Cost.

1 Introduction

The maritime environment is one of the most aggressive environmental exposure on the planet for reinforced concrete structures. If proper protective measures to this very aggressive environment are not taken the durability of materials and structures can be compromised. The building materials degrade when exposed to this environment, causing damages of diverse nature in the structures. This aspect has been seen in many structures and buildings that showed early deterioration in recent years [1].

To this end, new structures must be dimensioned, constructed and maintained to have adequate performance during construction, service life and dismantling [2].

The Viaduct of the Oil Terminal of the Port of Leixões is exposed to the aggressive waters of the

Atlantic, and is currently in a state of very advanced degradation, which would be expected since this structure was designed for a useful life of 50 years. Having been built in 1967 has already reached the 50 years of life. This life span could have been prolonged with regular maintenance and repairs, which by the existing records did not happen. Only in the year 1993 there was a rehabilitation of the structure, which for the environmental exposure that was found that was not enough to extend its life time.

Therefore, it is important to prepare a new project for the Viaduct of the Oil Terminal of the Port of Leixões, which according to current regulations should be designed for a life time of 100 years.

2 Viaduct of the oil terminal of the port of Leixões

The Viaduct and the Maritime Terminal of Oil Tankers of the Port of Leixões have their initial project dated 1967, which is supposed to be the execution date. This is a structure consisting of longitudinal beams and crossbeams all in prestressed reinforced concrete based on pillar piles, which support a beam tray with 33 independent spans of 10 m in length each. The structure between supports has an extension of approximately 380 m [3]. Figures 1 and 2 represent an aerial view of the Structure and a cross section.

Figure 1. Aerial view of Viaduct and Terminal

2.1 Maritime terminal

The Maritime Terminal is a port construction, with vertical support elements based on the rocky bottom. The support elements consist in the meetings, intermediate coffins and caissons [4]

On the vertical elements are based longitudinal beams, a total of 71 beams and cross beams, a total of 31 beams, forming a continuous grid. All beams have the same section, type I, and all are pre-stressed. The cross beams extend beyond the vertical support to both sides. At the nodes of the grid formed by the beams, a monolithic connection was established with the vertical support elements, in this case the caissons [4].

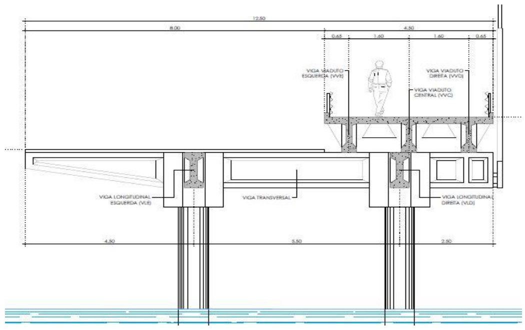

Figure 2. Cross section of the Viaduct and Terminal

2.2 Viaduct

The viaduct was constructed over the Maritime Terminal, consisting of 33 isostatic spans of 10.0 m each, with a reinforced slab, in which each section is composed of prefabricated and pre-stressed beams, with a type I section. The viaduct beams are supported on the cross beams of the terminal through the intermediary of neoprene devices [4].

2.3 Inspections and interventions made in the structure

The Viaduct of the Leixões Oil Terminal during its 50-year useful life was the subject of several inspections, the main ones occurred in 1993, 2005 and 2014 respectively, and one of those inspections, in 1993, led to a rehabilitation intervention of the structure [3].

During the course of these inspections, a survey was made, based on visual observations and photographic records, of the state of the structure, identifying the main pathologies presented in Figures 3 to 6 [3].

Figure 1. Longitudinal cracks in the bottom flange of the beam

Figure 2. Longitudinal cracks in the core of the beam associated with the pre-stress cables

Figure 3. Loss of section associated with the corrosion of the reinforcement

Figure 4. Beam ruin

In the preparation of the last inspection report, dated 2014, the methodology used to classify the pathologies present in the infrastructure was very similar to that used in the previous reports, so that it would be easier to evaluate the progression of the present faults of 2005 for 2014 since they were not initially treated, and these have continued or worsened over the years [3].

Thus, the severity of the present malfunctions follows the classification presented in Table 1.

Table 1. Degree of malfunctions

Identification	Degree of Damage
1	Visible but of little importance. Fissure of 1 to 2 mm. No concrete highlights
2	Some importance. Frankly visible from 3 to 5 mm. Concrete highlight without fall.
3	Very important damage. Cracks very open and with continuity on both sides. Highlight concrete with some drops. Corrosion of visible steels
4	Similar to 3 but for pre-stress cables

Due to the fact that no further rehabilitation interventions were carried out in the structure since 1993, it was possible to make a comparison of the evolution in the state of the same from 2005 to 2014 [3]. Table 2 shows the evolution in the number of pathologies of degree 3 and degree 4 between 2005 and 2014.

Table 2. Number of grade 3 and 4 pathologies in 2005 and 2014

		2005	2014
Pathologies of Degree 3	Terminal	7	24
	Viaduct	2	6
Pathologies of Degree 4	Terminal	14	17
	Viaduct	1	12

2.4 The maritime environment

Among the environments that exist on our planet the most aggressive for the reinforced concrete are the acid and saline environments. The physical and chemical characteristics of the marine environment are determinant for the durability of any material inserted in this environment so severe [5].

The various aggressive agents in the marine environment, whether of physical, chemical or biological origin, and their interconnection make this environment very hostile to common building materials, and careful consideration is needed for their convenient characterization when it comes to works over the sea or in a coastal strip where the aggressive effect is still felt. The reactions of the concrete in this type of environment are varied, being their cause of difficult characterization [5].

2.5 Studies and recommendations for the design phase

During the year 2016 a non-destructive study was carried out to characterize the concrete of the structure. For this purpose, tests were carried out with the objective of evaluating, essentially, the parameters of structure durability, in particular the state of passivation of the reinforcement in relation to the corrosion, and to evaluate the strength of the concrete [6].

Also, during 2016, based on the data from the above report, a study of the deterioration of the structure was elaborated through the introduction of this data into durability models. These models covered prescriptive and performance approaches, in which the second model distinguishes a deterministic model, according to Model Code 2010, a semi-probabilistic, according to the specification LNEC E465 (national standards) and two probabilistic, according to the same norms. Based on the deterioration prediction tools, design scenarios were also created, from which a list of minimum coatings was obtained to ensure a 100-year shelf life for a structure to be built in the area of the studied class [2].

For the design of the new structure was considered the project scenario according to standard LNEC E464 (national standards) in which durability is ensured by fixed values depending on the exposure class and the time desired life. The minimum recoating values, water / cement ratio, minimum cement quantity and minimum concrete strength class are presented based on the experience of numerous structures constructed in similar environments. It was considered exposure class XS3 - induced corrosion from seawater chlorides in tidal areas, surf or splashing - and lifetime of 100 years since it is an important structure, and where the standard states that for these cases, the minimum cover should be increased by 10 mm [2]. In this way the prescriptive values indicated in Table 3 are obtained.

Table 3. Prescriptive approach [2]

Type of cement	CEM IV/A; CEM IV/B; CEM III/A; CEM III/B CEM V; CEM II/B; CEM II/A-D	CEM I; CEM II/A
Minimum nominal cover (mm)	65 mm	65 mm
Maximum water / cement ratio	0,45	0,40
Minimum dosage of cement, C (Kg/m^3)	340	380
Minimum resistance class	C 35/45 LC 35/38	C 50/60 LC 50/55

3 Design of the slab of the Viaduct

For the design of this structure it was considered that the beams of the Viaduct are supported on the beams of the existing structure, the Maritime Terminal.

The first design solution consists entirely composed of a concrete structure with a concreted "in-situ" slab, and pre-stressed prefabricated beams with an "I" section, which is assumed to arrive at the job site with 90 days age, and it is considered that there is no continuity between the beams of each span of 10 m.

The second solution design corresponds to a composite structure, wherein the viaduct deck is constituted by a concrete slab in situ, and metal beams. In this solution, the conditions of the support beams are the same as the first solution, they are supported on the beams of the Maritime Terminal, and this solution is considered that there is continuity (connection) between the beams of each span of 10 m.

3.1 Actions on bridges and road viaducts

The determination of the actions on bridges and viaducts is a very complex task, because they have different natures. The form and intensity with which they act depends on several factors, such as geography, climate, type of use, etc. Briefly, they can be classified into the following types:

- Permanent Actions (G_i);
- Variable Actions (Q_i);
- Natural Actions: caused by wind, snow, earthquakes and others;
- Deformations;
- Accidental actions (A).

For this work they were just considered the most important for the checks in the Ultimate Limit State and Service Limit State and only permanent actions and variable actions being considered.

The quantification of permanent actions, a distinction was made between structural elements and non-structural elements.

To quantify the variables actions, this kind of bridges the actions caused by traffic are the most significant, so it is vital to consider a charging model that characterizes the effect of any type of vehicle capable of crossing the bridge. The EC1 defines several load models to be considered in the quantification of the variable actions.

3.2 Limit States

Structural safety and proper in-service behavior are two basic requirements in structural design. The first corresponds to the need to minimize the risk of partial or total collapse and the second is related to the proper functioning of the structure under normal conditions of use.

The current regulations consider the mandatory verification of two limit states, the ultimate limit state (ULS) and the service or utilization limit state (SLS).

In checking the ULS it is ensured that the structure does not collapse partially or completely.

The SLS is the verification of the durability and functionality of the structure, where failure to verify this limit results in a malfunction of the structure, but with damages that do not affect the functionality of the structure.

3.3 Combinations of actions

The EC0 does the security check in relation to the different limit states considering the possibility of the simultaneous and probable action of actions that provoke in the structure the most unfavourable effects for the same.

The calculation effort values are then determined from the combination of certain actions affected by their partial safety coefficients. EC0 defines two types of combinations: the fundamental combinations where the effects of permanent actions and variable actions are accounted for, and the accidental combinations that, in addition to the actions already mentioned in the fundamental combinations, also include accidental actions.

4 Viaduct Life Cycle Cost Analysis

Life Cycle Cost Analysis (LCCA) is an economic method of evaluation of projects in which all costs of owning, operating, maintaining, and ultimately demolishing are considered to be potentially important for this decision [7]. The LCCA allows comparative assessments to be made over a period of time, taking into account all relevant economic factors, both in terms of initial costs and future operating costs [8].

The LCCA is suitable for the evaluation of alternative asset building project that meets a required performance but which may have different initial costs, different operating costs, and possible different life expectations. The LCCA provides significantly better long-term cost evaluation of a project than other alternative economic methods, as they focus on upfront costs or on short-term operating costs [8].

Different costs occur at different points in the life cycle of an asset under construction. These costs cannot be compared or simply summarized due to the variable value of money over time. The present value represents the amount of money that would need to be invested today, at an interest rate equal to the discount rate, so as to be able to have the money available to meet the future cost at the time the expense is expected to occur [7].

$$PV = \frac{FV}{(1+d)^n} \tag{1}$$

where,

PV is the present value;

FV is the value in the future;

d is the interest rate;

n is the number of years in the future.

The life cycle cost analysis (LCCA) can be divided into three main groups: (i) construction cost (CC);

(ii) operating costs (OP); (iii) and end-of-life costs (EC). As indicated in expression (2).

$$LCCA = CC + OP + EC \qquad (2)$$

where the costs of maintenance and repair of the viaduct over the life of service time are included in operating costs and the cost of demolition and disposal of the resulting materials are included in end of life costs [8].

- Construction costs

Construction costs are all costs related to the viaduct construction process, and are usually calculated on the basis of unit costs and the map of quantities of materials required to construct the viaduct. It is assumed that these costs occur in year 0 of the viaduct life cycle [8].

- Operational costs

Operating costs are all costs that occur from the beginning of the opening of the viaduct to its end of life cycle. In the calculation of operating costs are included the costs of periodic inspections, costs due to periodic activities to maintain the viaduct condition at the required level, and costs associated with repair and replacement / rehabilitation activities [8].

- End-of-life cost

End of life costs are associated with partial or total demolition of the viaduct and waste removal to its final destination activities [8]. At this cost can be subtracted the value of the demolition materials, in case they have any value. For example, the steel can be sold for recycling, recovering some of the value invested in the demolition of the viaduct.

- Calculation method (discount rate)

Once it is estimating a cost over 100 years, these future costs over the life cycle of the viaduct can be discounted at present value.

The following expression (3) is used to calculate the Present Value for Life Cycle Cost Analysis (PVLCCA):

$$PVLCCA = \sum_{t=1}^{N} \frac{C_t}{(1+d)^t} \qquad (3)$$

where:

Ct sum of the relevant costs that occur in year t;

N number of years of the study period;

d discount rate used.

This turns values that occur at different times in the life cycle into a value in the present.

The discount rate is not a fixed value, and government agencies tend to use real discount rates in its analysis. Countries such as the UK, USA, Germany and Switzerland use values of 8%, 6% 3% and 2% respectively, where the larger the discount rate the lower the importance of long-term costs [8].

Rebitzer proposes the use of a discount rate that can vary between 0 - 10% [9].

For this analysis, was assumed a discount rate of 3.5%, which represents a quite acceptable value considering what is used by other European countries.

4.1 Cost of the life cycle

The cost of the viaduct life cycle is calculated using the expression (2) from which was calculated the cost of the life cycle to the solution 1 (concrete structure) and Solution 2 (composite structure), from the accumulated cost for year in the graph of Figure 7 for solution 1 and in Figure 8 for solution 2.

4.2 Variation of the discount rate

It is very important to note that the results presented above do not represent fixed values for the life cycle analysis, since a cost for a life cycle of 100 years is predicted where there are many variables to consider. One of the most important aspects to mention is the possible variation of the discount rate between 0% and 10%, which for the values presented above has a value of 3.5%, which is a very acceptable value for this analysis, but where a small variation in this rate represents major changes in the final life-cycle cost for the viaduct. Table 4 presents four values for the discount rate variation, presenting the life cycle cost for each solution, the percentage difference between the costs for each solution, as well as the percentage change in cost for different discount rates. The percentage of different costs for the variation of the discount rate is between the rates of 0% and 3.5%, between the rates of 3.5% and 5% and between the rates of 5% and 10%.

Figure 7. accumulated cost per year of the viaduct lifecycle (solution 1)

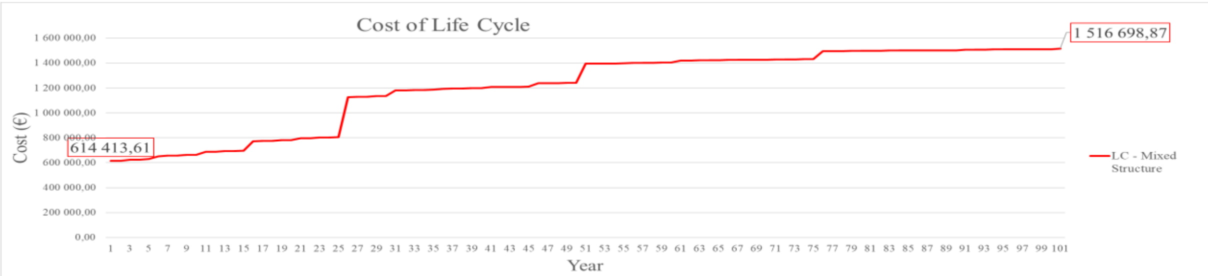

Figure 8. accumulated cost per year of the viaduct lifecycle (solution 2)

Table 4. Variation in discount rate

<table>
<tr><td>Discount rate</td><td colspan="2">0,0%</td><td colspan="2">3,5%</td><td colspan="2">5,0%</td><td colspan="2">10,0%</td></tr>
<tr><td>Concrete Structure (€)</td><td colspan="2">4 705 623,62 €</td><td colspan="2">1 411 235,91 €</td><td colspan="2">1 058 241,78 €</td><td colspan="2">652 412,48 €</td></tr>
<tr><td>Mixed Structure (€)</td><td colspan="2">4 578 326,08 €</td><td colspan="2">1 516 698,87 €</td><td colspan="2">1 185 042,60 €</td><td colspan="2">801 804,00 €</td></tr>
<tr><td>Cost Differences (%)</td><td colspan="2">-2,71%</td><td colspan="2">7,47%</td><td colspan="2">11,98%</td><td colspan="2">22,90%</td></tr>
<tr><td rowspan="2">Differences in cost between discount rates (%)</td><td>Con. Str.</td><td colspan="2">233,44%</td><td colspan="2">33,36%</td><td colspan="2">62,20%</td><td></td></tr>
<tr><td>Mix. Str.</td><td colspan="2">201,86%</td><td colspan="2">27,99%</td><td colspan="2">47,80%</td><td></td></tr>
</table>

5 Conclusions

The main objective of this work is the evaluation of the life cycle for different constructive solutions for the Viaduct of the Oil Terminal of the Port of Leixões. Two solutions were selected, one in prestressed concrete and the other using a composite steel / concrete structure. Figure 9 shows a graph comparing the life cycle analysis costs for each of the solutions studied.

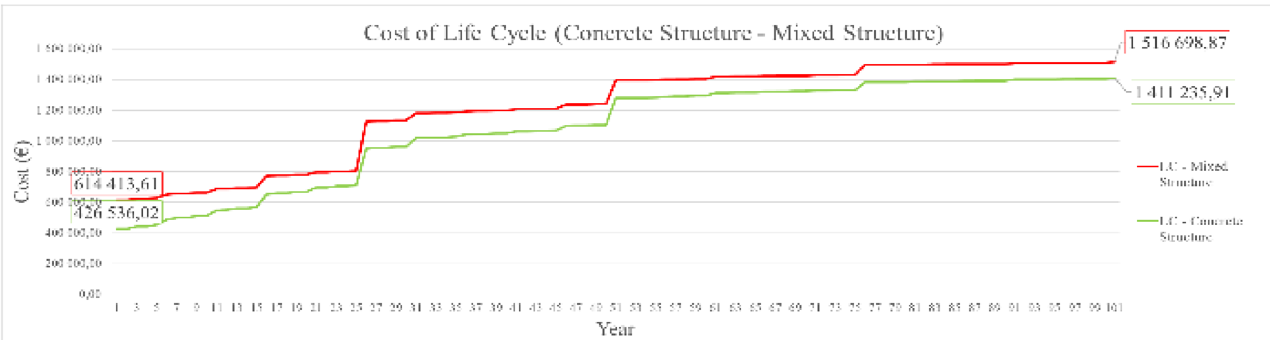

Figure 9. Analysis of the life cycle cost for both solutions

It can then be concluded that the structure design in concrete has a lower cost of life cycle, about 7.47% lower than the design solution to the composite structure.

Taking a more detailed analysis of the life cycle, the 3 main life cycle analysis groups (construction costs, operational costs and end-of-life costs) show that in relation to the construction cost the composite solution is more expensive, approximately 44.05% more than the concrete structure. In relation to the operational costs for the composite solution these are lower 9.11%. In the cost of end of life the cost for the composite structure is lower 12.30% in relation to the solution in concrete. It can then be said that although the composite solution has a higher life cycle cost, this is due to the fact that the construction cost for this solution is higher because the operational and end-of-life costs are lower in comparison with the concrete solution.

With the values presented it is understood the importance of making an analysis of the life cycle of the structures, which is not yet a reality in construction in Portugal. This is because in the cost of the life cycle of a structure, the cost of construction may represent a low value in relation to the cost of the total that the structure can have. For the case under study and at a discount rate of 3.5%, the construction cost for the concrete solution represents 30.2% of the life cycle cost, and in the composite solution the cost of construction represents 40.5% in the cost of the cycle of life.

This implies the importance of designing the life cycle of the structures, and the elaboration of a schedule of maintenance / repair and rehabilitation for the elements of the structure, in order to inform the owner of the structure, who will manage the funds in a way to be able to prevent and design in advance possible work needed to ensure that the structure reaches the useful life objective, in this case the 100 years.

6 References

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