Life cycle cost analysis of some reinforced concrete repairing techniques

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Abstract

The concern over the deterioration of reinforced concrete structures exposed to marine environments, with the consequent increased awareness for the need to repair these structures and ensure their safety, is widespread in recent years. As the “economic” factor plays an obvious and essential role in the decision-making process aimed at evaluating the best repairing techniques to adopt, the present work is intended to assist owners of deteriorated reinforced concrete structures in their choice of the most cost effective repair alternatives with the aim of achieving the lower life-cycle costs possible.

Two real structures were studied with the aim of comparing the costs of the following three different prevention and repair techniques:

− Use of inox steel instead of current steel.
− Repairing by steel repassivation and replacement of the damaged concrete layer;
− Cathodic protection.

Furthermore, in order to determine the consequences of some specific situations in terms of life costs the following situations were also studied:

− The influence of a reduction of the reinforcement cover, for a given concrete quality;
− The influence of a reduction of concrete quality, for a given reinforcement cover.

Keywords: Service life, costs, corrosion

1. Introduction

Reinforced concrete is a relatively recent material whose behaviour, although well known and studied from a structural point of view, is not yet perfectly understood in durability terms. This latter aspect is particularly important in aggressive environments, such as the marine one, since there are several cases of structures experiencing early deterioration, resulting in poor durability and leading to increases in maintenance and repair costs.

Reinforced concrete’s weak behaviour in marine environments is often the result of the penetration of chlorides from the seawater leading to corrosion of the steel reinforcement when these ions’ concentration reaches a certain threshold. Hence, the corrosion process causes a reduction of the steel cross-section and the formation of highly expansive reaction products that lead to cracking and to spalling of the concrete cover.

Although it is well known that marine environments lead to faster degradation of concrete, there are many examples of structures where the deterioration is indeed accelerated by poor construction quality or inadequate design (ex: bad choice of the concrete’s composition, or a wrong definition of the concrete’s cover). These situations, although sometimes resulting from insufficient information about the parameters influencing the degradation process, are often and unfortunately derived from economic pressures to reduce initial investment costs and increase competitiveness in a very highly competitive market; however they normally end-up by yielding higher life-cycle costs, as these
structures need more frequent and earlier repairs in order to guarantee their structural safety as well as the safety of their users.

Therefore, when one has to decide whether to choose a higher or a lower material quality, or a certain type of repairing technique, a life cycle cost analysis must be performed in order to ensure that the most economical solution is selected, taking into account a variety of different types of costs such as: the initial construction or investment cost, the recurring inspection and maintenance costs, the regular restoring and repairing costs, the user costs or the failure costs.

2. Main deterioration causes of marine exposed reinforced concrete structures

When exposed to marine environments, reinforced concrete structures are badly affected by the corrosion of the concrete reinforcement bars, which occurs almost entirely due to the presence of chlorides in the seawater.

Four different zones should be considered when identifying the main causes of reinforced concrete deterioration in a marine environment: the submerged zone, the tidal zone, the spray zone and the atmospheric zone.

![Fig. 1 - Possible degradation mechanisms acting on concrete exposed to a marine environment](image)

**Submerged zone:** As the concrete is permanently saturated, there is not much oxygen near the steel and, therefore, corrosion does not play an important role in the deterioration process. The main cause of the degradation in this zone is the chemical attack which can result in the weakness and increase of the porosity of the cement folder (if the aggressive agent is the carbon dioxide or the magnesium chloride), or in the development of expansive chemical substances that can lead to the cracking of the concrete cover (if the contamination is caused by sulphates).

**Tidal zone:** The main deterioration causes are the same as for the submerged zone since only the superficial concrete dries.

**Spray zone:** As the concrete in this zone is not saturated, the diffusion of oxygen occurs with higher speeds and, if the soluble chlorides can penetrate the concrete right up to the reinforcement, there will be a disruption of the thin protective film of iron oxide that protects the steel and the corrosion process can take place. This results in the formation of rust that can lead to an increase in the original steel’s volume causing the cracking and spalling of the concrete. In addition to the degradation caused by the steel corrosion, the erosion due to the impact of waves can also occur in this zone.

**Atmospheric zone:** In this zone, steel corrosion caused by the chloride attack constitutes the main cause for the concrete deterioration; nevertheless, carbonation can also occur.

3. Evolution of reinforced concrete’s deterioration

The determination of the chlorides penetration rate in concrete is essential when predicting, without great expenditures, the ideal moment for repairing a structure.

In this stage, it is usual to consider that the best time to react is before the end of the initiation phase of Tuutti’s model, which can be defined as the time when the chlorides concentration next to the
concrete’s reinforcement reaches the critical threshold, leading to the disruption of the oxide film protecting the steel.

This assumption is based on the fact that, when corrosion takes place due to concrete’s contamination by chlorides from seawater, it can occur at such high rates that the propagation phase is reduced to some months and there will be no time to safely repair the structure (there are cases of structures where a corrosion rate of 1000 µm/year has been measured).

To estimate the moment at which this disruption occurs, it is common to use Fick’s Laws which, considering that the diffusion coefficient and the surface chloride’s content are constant with time, leads to the following formula:

\[
C(x, t) = C_i + (C_S - C_i) \left[ 1 - \text{erf} \left( \frac{x}{2\sqrt{D.t}} \right) \right]
\]

Where:
- \(C(x, t)\) Chloride content at depth \(x\) and time \(t\), \([\text{kg/m}^3]\);
- \(C_i\) Initial chloride content in the concrete admixture, \([\text{kg/m}^3]\);
- \(C_S\) Surface chloride content, \([\text{kg/m}^3]\);
- \(\text{erf}\) Error function;
- \(x\) Distance, m;
- \(D\) Chloride coefficient, \([\text{m/s}^2]\);
- \(T\) Time, [s]

Although this formula is commonly used in simple cases, it can lead to unrealistic results, especially when long-term predictions based on short-term tests are needed. Therefore, in the present work, a different formula has been used in order to take into account the variation of the chloride’s diffusion coefficient and of the surface chloride’s content with time:

\[
C(x, t) = C_i + (C_S(t) - C_i) \left[ 1 - \text{erf} \left( \frac{x}{2\sqrt{D(t).t}} \right) \right]
\]

\[
C_S(t) = C_{ref} \left( \frac{t}{t_{ref}} \right)^n
\]

\[
D(t) = D_{ref} \left( \frac{t_{ref}}{t} \right)^m
\]

Where:
- \(n, m\) Empiric coefficients that depend on the concrete’s quality and on its exposure conditions and can be obtained by a statistic regression of some \textit{in situ} tests, performed at different times;
- \(t_{ref}\) Reference time;
- \(C_{ref}\) Surface chloride content measured in the reference time, \([\text{kg/m}^3]\);
- \(D_{ref}\) Chloride coefficient measured in the reference time, \([\text{kg/m}^3]\);

Other types of formulas may be used, to take into account the variation of the chloride’s coefficient with temperature but, in the present work, this variation has not been considered.
4. Inspection and evaluation of the deterioration’s degree

The definition of a maintenance plan (during the design phase) encompassing regular structural inspections is the most appropriate approach to cope with deterioration, as it allows timely forecasting any deterioration problems, making it possible to adopt a preventive repair strategy. Unfortunately, this is seldom the case, leading to late detection of problems and much more extensive and expensive repairs.

In the case of reinforced concrete structures exposed to a marine environment, inspections should focus on the determination of the possible causes of deterioration and on the characterization of the concrete’s properties that can have an influence on the penetration of chlorides such as its mechanical properties, its permeability or porosity, the thickness of the concrete’s cover or its resistivity.

To determine the deterioration causes, the possible exterior signs of concrete’s chemical attack, the depth of carbonation and the chlorides’ concentration at various depths must be identified. It may also be useful to determine the corrosion rate, if it has already started, so that the deterioration’s evolution can be estimated.

5. Common repair techniques

Corrosion in chloride contaminated concrete leads to the destruction of the protective oxide film normally developed on steel surfaces in alkaline environments. If the chlorides could be removed from both the concrete and the steel, and providing the PH is high enough to re-establish the protective film, the problem would be solved.

Traditionally, this has been done by removing the concrete layer having a chloride concentration exceeding 0.3% to 0.4% of the cement’s content and by replacing it with a new material (in literature, this is usually referred as “patching”). This repair technique is not only work-intensive, but it may even produce negative structural consequences. As an alternative, electrochemical methods, usually allowing rehabilitation without extensive breaking-out of the structure, seem particularly suited for repairing structures with high architectural or historical value.

5.1. Electrochemical repairs

The main electrochemical techniques used for reducing corrosion on reinforced concrete structures are:

− Cathodic protection;
− Electrochemical re-alkalinisation;
− Chloride extraction (desalination).

The main common principle in these three methods is the use of a direct current flowing through the concrete (electrolyte) to the reinforcement (cathode), by means of an external conductor (anode). This will lead to the repassivation of the rebars due, in the first technique, to the polarization of the reinforcement to a greater negative potential, to the removing the chlorides from the concrete’s pores in the second or to restoring the alkalinity of the pore’s solution in the last one. The final common result of these three repair methods is the mitigation or the halting of the corrosion process.

These methods have, therefore, practical details in common, the main differences between them being the amount of current flowing through the concrete as well as the duration of the treatment.

5.1.1. Cathodic protection

Cathodic protection is the only non-temporary electrochemical treatment capable of repairing highly deteriorated structures suffering from reinforcement corrosion due to chloride contamination.
This repair technique makes the metal behave as cathode by shifting its potential to higher negative values and resulting in a reduction of corrosion levels to negligible values. This technique also has the beneficial effect of cathodic protection by the production of hydroxyl ions that increase the PH of the pore’s solution with the subsequent reforming of the passive protecting film on the reinforcement steel’s surface.

In applying cathodic protection, either a very active metal (sacrificial anode) can be used auto-polarizing the metal to cathodic values when connected to the reinforcement bars or, alternatively, an inert anode with DC applied connected to the reinforcement bars can be employed.

5.1.2. Electrochemical re-alkalinisation

Since corrosion in carbonated concrete is caused by the disruption of the passivating film at low PH levels, one way to counter the problem is to find a method that sufficiently raises the PH allowing the oxide film to reform. Electrochemical re-alkalinisation repair is one of the possible ways to achieve this.

Re-alkalinisation is a temporary treatment particularly suited for structures with a special architectural value, such as monuments, as it does not damage the original structure.

The main principle of this repair technique is the same as for all the electrochemical treatments and the duration, applying a current of around 0.8 to 2 A/m² of concrete surface, can vary from 1 to 2 weeks.

During the treatment, the electrolyte is transported through the carbonated concrete by electro-osmosis or ion migration processes and a highly alkaline solution is generated inside the concrete.

5.1.3. Chloride extraction (desalination)

Desalination is an electrochemical repair method suited for structures suffering from reinforcement corrosion induced by chloride’s contamination. This technique having a great efficiency in the treatment of structures where the deterioration stage is not advanced, is particularly suited for repairing structures with special architectural value.

As in electrochemical re-alkalinisation, desalination also involves physical-chemical processes, the two most important being the electrolysis and the ionic migration. During the treatment, electrolysis results in the cleaning of the steel surface, in the generation of high PH values and in the decrease of the Cl/OH ratio near the steel (disfavouring corrosion). Ionic migration, instead, results in the removal of chloride ions from the concrete and in supplying the counter-ions required, after the current is switched off, for the changes in PH and Cl/OH ratio to be retained.

This treatment lasts of 6 to 10 weeks, applying a current of 0.8 to 2 A/m² of concrete surface.

5.2. Patch repairs

The replacement of contaminated concrete for a new material is the traditional way of repairing deteriorated concrete structures exposed to marine environments. This treatment results both in the repassivation of the reinforcement steel and in an increase of the binding properties of the concrete cover.

The efficiency of this repairing technique depends highly on the quality of the executed works, as although there are examples of structures where the repairs lasted for more than fifty years, there are also cases where the treatment was so badly carried out that problems re-appear few years only after the repairs.

One of the aspects affecting the repair quality is whether all the contaminated concrete is removed or only some parts of it. The former is always technically better since it generates a longer service life however, as its initial cost is also higher, the latter is often preferred with the drawback of possible
formation of incipient anodes that will subsequently increase the deterioration of the zones neighbouring the repaired area, quickly jeopardizing the repair efforts.

5.3. Corrosion inhibitors

The use of corrosion inhibitors is one of the techniques that may be used on reinforced concrete structures exposed to marine environments since, when applied in the initial admixture, these inhibitors help preventing the onset of corrosion and, when surface-applied, can decrease the corrosion rate.

Surface-applied inhibitors are designed to penetrate the concrete in order to suppress or control the corrosion rate. However, as the diffusion of these products often occurs at slow rates, this may render them inefficient.

6. Principles of an economical analysis

The selection between different technically adequate alternatives is usually difficult but can be eased through the help of life cycle cost analysis of each alternative.

When estimating the total cost of a repair strategy, the initial step is to identify all the activities that will probably be realized during the service life of the structure in order to estimate their actualized value at the present time. The most common costs taken into consideration are the construction costs ($C_C$), the maintenance costs ($C_M$), the inspection costs ($C_I$) and the repair costs ($C_R$). There are however other types of costs possibly relevant to the analysis, although more difficult to define as, for instance, the value of human lives possibly lost in an accident or the destruction of structures having a cultural or historical value (generally named as failure costs, $C_F$), or even the user costs created by service disruption caused by the repair works on a bridge.

Therefore, one of the formulas that may be used for a life cycle cost analysis is:

$$C_T = C_C + C_I + C_M + C_R + C_F + C_{Other costs}$$

Each of the five parameters in the above formula should be adjusted using the formula below to the reference time, which is usually the moment when the study has been performed:

$$C_i = \frac{C_{i,j}}{(1 + r)^j}$$

Where $r$ is the estimated actualisation rate, $j$ is the number of years between the date when the investment is made and the present time when the study is being conducted and $C_{i,j}$ is the cost to be incurred during that year.

The estimation of future actualisation rates is one of the difficulties of this sort of studies as they vary from country/company to country/company.

In the present work, the actualisation rate was assumed to be constant during the whole analysis period and equal to the average discount rate for European Union Countries between 1980 and 1999 (see Fig.2).
7. Case studies

7.1. Repairing of the Pumping Station located at the Mitrena Shipyard

This facility, located at the Mitrena Shipyard (in Setubal, Portugal), has been in service for more than 34 years. Due to the proximity of two docks, this facility is in constant contact with chlorides from seawater and reinforcement corrosion has already induced some damages. In the year of 1992, this structure was repaired by replacing the contaminated concrete with new material; nevertheless, in 2007, it will again be necessary to repair the structure since several new areas are, once more, evidencing deterioration (cracking, delaminating and spalling of the concrete cover).

In this study, three repair solutions have been evaluated. The first option envisaged was identical to the solution adopted in 1992 (patch repair) and needs to be repeated every 15 years, as it is unfeasible to remove all the contaminated concrete (the estimated repair area in each treatment is about 400m²). The repair costs were estimated at 435€/m². The second repair solution envisaged was cathodic protection. The repair costs, were estimated at 100€/m², 150€/m² and 200€/m² and the maintenance costs were assumed to be approximately 10% of the repair costs. The last option is hypothetical and is intended to simulate the possibility of replacing a certain quantity (20%, 30% or 50%) of the carbon steel by inox steel during the construction of the structure. This approach will lead to higher initial costs, but inspection, maintenance and repair costs during the service life of the structure will be diminished.

![Fig. 3 – Aerial view of the Mitrena Shipyard (image obtained from Google Earth)](image)

![Fig. 4 - Life cycle cost analysis of three repair strategies (actualisation rate of 2%)](chart)

This case study shows that a preventive strategy (replacement of some carbon steel for inox steel) yields substantially lower total costs. It is also visible that the choice between a repair with cathodic protection or with patch repairs depends on the estimated cost per m² for each solution.
7.2. Repairing a concrete pier located at the Tagus River

This reinforced concrete structure was built in 1930; it is approximately 45m long and 24m wide.

A detailed inspection was carried out in 2006 as the structure presented high levels of deterioration due to the penetration of chlorides into the concrete’s pores.

As in the previous case, three repair strategies were studied (patch repair every 25 years, cathodic protection and the hypothetic construction of the structure in 1930 with a certain amount of inox steel instead of carbon steel).

For this case, an initial costs estimation of 730.000€, for the first option, and 500.000€ for the second option, had already been made by a construction company.

![Fig. 5 – Aerial view of the Mitrena Shipyard (image obtained from Google Earth)](image)

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For this case, an initial costs estimation of 730.000€, for the first option, and 500.000€ for the second option, had already been made by a construction company.

![Fig. 6 - Life cycle cost analysis of three repair strategies (actualization rate of 2%)](image)

The analysis of this case study reinforces the idea that a preventive strategy leads to substantially lower total costs during its structure’s service life (Fig. 6 and Table 2 show that the cost of replacing 50% of the carbon steel for inox steel during the construction phase, leads to about 50% life cycle cost savings when compared to the actual case where the structure has been built with carbon steel only and is repaired in 2007 with the installation of a cathodic protection system or with patch repairs).

### 7.3. General case

The objective of the last case study is to analyze the influence of the concrete’s cover thickness and of the concrete’s quality in the total cost of a structure during its service life.

For this purpose, a general sample of reinforced concrete (with a thickness of 0.20 m and a surface area of 1 m²) was used.
In this study, two different types of concrete were considered:

- Concrete B1 – 300kg of a Type 1 cement for each m$^3$ of concrete; a/c ratio of 0.5; Approximately a C25/30 concrete;
- Concrete B2 - 425kg of a Type 1 cement for each m$^3$ of concrete; a/c ratio of 0.3; Approximately a C40/50 concrete;

As these types of concrete had already been studied in different environments, it was possible to calculate the parameters $D_{\text{year}}$, $C_S$, $t_{\text{year}}$, $n$, and $m$.

Additionally, a life cycle cost analysis was made for two different hypotheses:

- Hypothesis 1: The concrete’s cover has an average thickness of 0.03m and the thickness of the sample is 0.20m (Fig. 7);
- Hypothesis 2: The concrete’s cover has an average thickness of 0.06m and the thickness of the sample is 0.26m (Fig. 8);

Using equation (2) it was possible to determine the end of the initiation period, for each sort of concrete and for different types of thicknesses of the concrete’s cover. These results are presented in Table 3 and Table 4 below.

<table>
<thead>
<tr>
<th>Concrete's cover thickness</th>
<th>Atmospheric/Splash zone</th>
<th>Atmospheric zone</th>
<th>Tidal Zone</th>
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Table 3 - Time until the end of the initiation period for concrete B1

<table>
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<th>Atmospheric zone</th>
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Table 4 - Time until the end of the initiation period for concrete B2

Taking into account that the application cost for concrete B1 is 70€/m$^3$ and 90€/m$^3$ for the concrete B2, that carbon steel costs are approximately 0.9€/m$^3$, that the cost of formwork is 15€/m$^2$ and that the repair costs are 150€/m$^2$, the life cycle costs for both hypothesis can then be compared as follows.
With this study we can conclude that an increase of the concrete’s cover thickness yields a lower total cost for the structure, as repairs are not so often required during its service life. In the present example, the total cost can be reduced by 45€/m² to 65€/m², when increasing the concrete’s cover thickness.

A similar conclusion can also be made for an increase in concrete’s quality as, if using a concrete B2 instead of a concrete B1, the total costs can be reduced by 15% to 20% (23€/m² to 38€/m²) for the first hypothesis and by 10% to 45% (9€/m² to 68€/m²) for the second one.

It can also be seen that an inferior concrete’s covers thickness leads to a quick increase of the structure’s total cost, as there are many areas that will need to be repaired due to the easiness of the chloride’s penetration into the concrete. After this big increase in the total cost, this tendency starts to decrease, as it was considered that all the repaired areas will have a long service life and it will not be necessary to repair them again in the future.

In this study, other deficiencies (like cracking) were not considered but they may have a great influence in the durability of the structure.

8. Conclusion

With the present work it is demonstrated that the timely adoption of a preventive maintenance strategy, rather than a reactive maintenance strategy, for a concrete structure exposed to a marine environment yields lower total life cycle costs for that structure.

It is also proven that in this type of environment, being highly aggressive to reinforced concrete structures, it is preferable to opt for a thicker reinforcement cover as well as a higher concrete quality in order to minimize the repairing costs during the structure’s whole service and, as such, reduce the life cycle costs.