Abstract

Corrosion is an inherent phenomenon of metallic structures. It causes damage due to loss of material and subsequent reduction of strength capacity. Consequently, this phenomenon has such relevance that it is not possible to neglect its effects. In order to mitigate the cons of corrosion, it is common the use of protection systems. These systems consist of coatings that can be made from organic or inorganic materials.

Given the wide range of products available on the market and consequent uncertainty about their properties and durability, it is necessary to systematize their selection method. In this context, standards and recommendations from several international entities are elaborated to promote a methodology for designing the protection solutions.

The aim of this dissertation is to synthesize anticorrosive protection solutions of steel from metallic structures, the analysis of specification methodologies and the study of solutions used in Portugal. To achieve them, it was performed a collection of bibliographic information which allowed the synthesis and characterization of protection methods. In order to comprehend and compare the prescriptive methods, standards from several entities were analysed. Finally, considering the information collected, six case studies of metal structures protected by anticorrosive paints were performed. This analysis allowed to conclude that in some cases, the prescription of the anticorrosive systems is overlooked in the design phase and it is delayed to a posterior one. Comply with standards such as ISO 12944 in the prescription of anticorrosive paints lead to solutions with well-known properties.

Keywords: Corrosion protection, anticorrosive paints, durability, coatings, corrosion.

1 Introduction

Corrosion has a significant impact on developed countries. It is estimated to have a cost of 2.5 trillion U.S. dollars, which is equivalent to 3.4% of global Gross Domestic Product (GDP) of 2013. Implementing good practices of corrosion protection can lead to savings between 15 and 35% of the presented values (NACE INTERNATIONAL, 2016).

Generally, corrosion protection systems consist of coatings that can be organic as anticorrosive paints or inorganic as metallic coatings. Their purpose is to reduce the corrosion rate of metallic structures and therefore, increase its durability. With the introduction of volatile organic compounds (VOC) limitations
in the 90’s, the whole paints industry has suffered a major change. This legislation caused an outbreak of new products to replace the old ones that had already well-known properties and durability. These new technologies have been developed through the years and nowadays, paints like high performance anticorrosive paints and smart coatings emerged (Sorensen, et al., 2009).

The main objective of this dissertation is to describe some important topics regarding anticorrosive protection and the presentation of the national panorama. In this study it will be performed a bibliographic research about anticorrosive systems, their general properties, specification methods and the presentation of six case studies of anticorrosive system specifications. Three of these case studies were from private initiative, while the remaining three cases consisted of bridges that belong to the public sphere.

2 Corrosive environments

An anticorrosive system may exhibit different performance and durability according to the environment that it is exposed. Therefore, an anticorrosive coating specification needs to attend the aggressiveness of the environment. Corrosive environments can be classified into three categories: immersion, splash zone and atmospheric as illustrated in Figure 1.

<table>
<thead>
<tr>
<th>Outdoor exposure</th>
<th>Atmospheric</th>
<th>Splash zone</th>
<th>Immersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marine</td>
<td>Industrial</td>
<td>Rural</td>
<td>Soil</td>
</tr>
</tbody>
</table>

*Figure 1 – Classification of corrosive environments.*

Atmospheric exposure may present a significant variety of conditions. In these environments, metallic structures can be exposed to aggressive agents such as ultraviolet radiation, heat, moisture or salts. The level of aggressiveness of these environments depends mainly on the distance to the sea and pollution levels (Sorensen, et al., 2009). Because of these facts, atmospheric environments classification is important in order to adapt each protection system to the specific aggressive agents and, consequently, to better specify anticorrosive systems. In Table 1 is presented the corrosivity categories of ISO 12944, the material consumption rates and examples of typical environments.

Structures located near the waterline of the sea are exposed to an extremely aggressive environment. This is the designated splash zone that has a very high corrosion rate due to alternated periods of moisture and dryness. It combines an oxygen-rich atmosphere with the continuous supply of electrolyte
with high chloride content. Thus, this environment leads to an accelerated degradation of coatings (Bayliss & Deacon, 2002) (Sorensen, et al., 2009).

<table>
<thead>
<tr>
<th>Corrosivity category</th>
<th>Loss of material by corrosion</th>
<th>Environmental examples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass loss (g/m)</td>
<td>Thickness loss (µm)</td>
</tr>
<tr>
<td>C1 - very low</td>
<td>≤10</td>
<td>≤1.3</td>
</tr>
<tr>
<td>C2 - low</td>
<td>&gt;10 to 200</td>
<td>&gt;1.3 to 25</td>
</tr>
<tr>
<td>C3 - medium</td>
<td>&gt;200 to 400</td>
<td>&gt;25 to 50</td>
</tr>
<tr>
<td>C4 - high</td>
<td>&gt;400 to 650</td>
<td>&gt;50 to 80</td>
</tr>
<tr>
<td>C5-I - very high (industrial)</td>
<td>&gt;650 to 1500</td>
<td>&gt;80 to 200</td>
</tr>
<tr>
<td>C5-M - very high (marine)</td>
<td>&gt;650 to 1500</td>
<td>&gt;80 to 200</td>
</tr>
</tbody>
</table>

Structures immersed in water or buried in the soil are exposed to an aggressive environment that requires high standards for the corrosion protection method. In these conditions, corrosion rates on immersed structures depend mainly on factors such as temperature, pH, content of dissolved gasses or salinity. The aggressiveness of soil on buried structures is primarily influenced by the type of soil, humidity, salt and oxygen content, bacteria and pH. Although it is difficult to classify these environments, ISO 12944 specifies three corrosivity categories: Im1 for immersed in fresh water, Im2 for structures immersed in seawater and Im3 for structures buried in soil (Sorensen, et al., 2009) (Ramires, 2009).

3 Surface preparation

Surface preparation plays an important role on the long-term performance of a coating as it influences the ability of adhesion between the substrate and the material applied. The majority of organic coatings adhere to a surface by a mechanism of polar adhesion which is helped or reinforced by mechanical adhesion. Polar adhesion is only effective to a molecular distance between steel and the paint film, therefore contaminants like dirt oil or water can effectively nullify all adherence. Alternatively, mechanical adhesion is helped by roughening of the surface and, consequently, the surface area. Another important factor is the stability of the substrate as, for example, mill scale, old paint or powdery layers of dirt can detach from the substrate and cause loss of adhesion (Bayliss & Deacon, 2002).

To obtain surfaces suitable for the application of coatings there are methods that eliminate contaminants as oil, grease, rust or dirt and to provide the required profile. ISO 12944-4 sort these methods into three categories: water, solvent and chemical cleaning; mechanical cleaning; flame cleaning. The first category of referred methods is useful for cleaning contaminants like oil, grease, water soluble material and loose rust while the mechanical cleaning, including blast-cleaning, is an effective method to remove
well adherent contaminants like rust or old paint films. Flame cleaning is a deprecated method that allows to obtain a level of cleanliness between the obtained from manual methods and blast-cleaning (ISO, 1998) (Bayliss & Deacon, 2002).

In order to standardize surface preparation, ISO 8501 identifies four levels of mill scale and rust that are commonly found on surfaces of uncoated steel. Furthermore, it also identifies certain degrees of visual cleanliness after surface preparation of uncoated steel surfaces and of steel surfaces after total removal of any previous coating. These degrees are defined by written descriptions together with pictographic examples. Surfaces prepared by blast-cleaning are classified with the letters “Sa” and consist of four grades, sorted from the lowest depth of cleaning to the highest depth: Sa 1; Sa 2; Sa 2 ½; Sa 3. Surfaces prepared by hand and power tools are divided into two classes, St 2 and St 3, the latter corresponding to a surface with a more in-depth preparation (ISO, 2007).

4 Anticorrosion protective systems

The protective systems of metal structures against corrosion consist of different layers of barriers between the metal and the environment, such as organic, metallic coatings or a combination of these two types, designated duplex system. Cathodic protection systems may also be used with or without simultaneous application of coatings or other barriers, especially in structures buried or placed in water, particularly in seawater (Perneta, et al., 2010).

In the process of corrosion of steel elements, oxygen reacts with iron, the largest constituent of steel, forming iron oxide. For this reaction to occur it is necessary the existence of three elements, a cathode, an anode and an electrolyte, forming an electrochemical cell. In this cell the anode is the negative electrode where the oxidation occurs (corrosion), the cathode is the positive electrode and the electrolyte the medium by which it crosses the electrical current (Figure 2a) (Cicek & Al-Numan, 2011). The role of anti-corrosion protections is to prevent or minimize the existence of these three elements simultaneously, in order to reduce the corrosion rate.

4.1 Metallic coatings

The most used metallic coatings are zinc-based and can be applied through hot-dip galvanising, metal spraying and less commonly with sherardizing or electroplating. Galvanising consists of the immersion of the steel element in a molten zinc bath that creates adhesion to the substrate by forming zinc-iron alloys with a growing zinc content (Figure 2b). The metal spraying consists on the projection of metal microparticles with compressed air through a pistol that has a heat source, merging the raw material from powder or yarn. The adhesion to the substrate through this method is guaranteed only mechanically, as opposed to galvanising (Bayliss & Deacon, 2002).

These types of coatings protect the substrate due to the formation of a physical barrier against aggressive agents. On the other hand, they also confer cathodic protection, since zinc has a greater
oxidative potential, suffering corrosion instead of steel. Additionally, in the case of damage to the coating, the substrate does not suffer corrosion due to the deposit of corrosion products formed from zinc that creates a barrier to these agents.

Figure 2 – a) Illustration of corrosion process (Lower, 2017) b) Cross section of galvanized steel (MICHA, 2014).

4.2 Anticorrosive paintings

A paint is a liquid, pasty or solid pigmented composition that, when applied in a thin layer on the appropriate surface, in the state in which it is supplied or after dilution or dispersion in volatile products, converts in a solid, continuous, stained and opaque film (IPQ, 1982). The protection conferred by these coatings is due to the formed film, which, when properly chosen and applied can prevent the action of degradation of aggressive agents (Marques & Rodrigues, 2000).

A paint is a mixture of three major components: a binder, responsible for solid film formation; a solvent, that is responsible for binder dissolution and evaporates during the curing process; and pigments that are insoluble particles by the solvents, responsible for giving the dry film certain properties. There are also additives, that are substances added in small percentage with the objective of improving a particular characteristic (IPQ, 1982).

The binder is responsible for important characteristics of the paints such as adhesion, cohesion, mechanical resistance or permeability and for this reason the paintings are designated according to their binder. There are two main types of paints, taking into account the drying process: physical drying and chemical drying. The physical drying paints generate the film through the physical evaporation of the solvent and its binder does not undergo chemical transformations, resulting in reversible paints, susceptible to solvents with reduced dependence on temperatures for film formation. Chemical drying paints form their films through the chemical reactions of its constituents and result in high chemical resistance coatings (Ramires, 2009). In Figure 3 the different types of binders are presented according to their curing process.

The paintings protect the substrate through three mechanisms: barrier effect; inhibitor effect and galvanic effect. Barrier protection consists of preventing aggressive species to reach the substrate by the coating system with low permeability for liquids, gases, and ions. Inhibitive coatings protect the substrate with the build-up of a protective layer containing insoluble metallic salts, which prevent the transport of aggressive species. Galvanic mechanism protection relies on a metal or alloy coating that
is electrochemically more active than the material to be protected suffering corrosion instead (Sorensen, et al., 2009).

Currently, there is a high focus on the development of coatings with improved properties and more durability, such as smart paints with self-healing capacity. There are two approaches to promote the self-healing capacity (Montemor, 2014):

1. Particle encapsulation with the ability to change the properties of the paint.
2. Manipulation of paint matrix composition with functional groups.

These are the so-called smart paints that consist in a coat that changes its properties in response to external stimuli. The particles responsible for these properties changes are involved by polymeric microcapsules. When the coating is damaged by the radiation, physical or chemical actions, these capsules release the inhibiting agents act on the site creating a passive barrier (Cotting & Aoki, 2015).

5 Standards analysis

Normative documents have the aim of providing information for the appropriate choice and execution of a paint system. In the present research it was analysed five documents: ISO 12944; AS/NZS 2132; SAES-H-001; SSPC Manual and AR 82.

There is a generic methodology in the specification of a paint system in these documents. Generally, it is necessary, in the first place, to classify the environmental exposure. Given that information there are recommended paint systems. Some documents have in consideration the expected durability to the selected method of protection.

5.1 ISO 12944 - Paints and varnishes - Corrosion protection of steel structures by protective paint systems

ISO 12944 is one of the most known and used normative documents related to anticorrosive painting. Its methodology to select a protection system can be summarized into three steps:
1. Definition of the corrosive environment according to ISO 12944-2, which were presented in section 2.

2. Definition of the desired durability: low for a period between 2 to 5 years; medium for a period between 5 and 15 years; high for a period superior to 15 years.

3. Selection of a paint system according to the previous points.

The paint systems presented in this document also contain information regarding the minimum preparation grade according to the visual ISO 8501. In Figure 4 is illustrated an example of some paint systems for an C5-I environment with its required surface preparation and durability.

<table>
<thead>
<tr>
<th>Paint System No.</th>
<th>Surface preparation grade</th>
<th>Priming coat(s)</th>
<th>Top coat(s) including intermediate coat(s)</th>
<th>Paint system</th>
<th>Expected durability (see 5.5 and ISO 12944-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>56.01</td>
<td>x</td>
<td>CR</td>
<td>AY, CR, PVC, 2 120</td>
<td>Low</td>
<td>200</td>
</tr>
<tr>
<td>56.02</td>
<td>x</td>
<td>EP, PUR</td>
<td>1-2 80</td>
<td>Medium</td>
<td>200</td>
</tr>
<tr>
<td>56.03</td>
<td>x</td>
<td>Misc.</td>
<td>3 200</td>
<td>High</td>
<td>280</td>
</tr>
<tr>
<td>56.04</td>
<td>x</td>
<td></td>
<td>1-2 80</td>
<td></td>
<td>320</td>
</tr>
</tbody>
</table>

5.2 Other standards

Several normative documents were analyzed with the purpose of understanding the methodology of specification of anticorrosive coatings:

- AR 82 – USDA Natural Resources conservation service (elaborated by the US Department of Agriculture);
- SSPC Painting Manual Fourth Edition (elaborated by The Society for Protective Coatings);
- SAES-H-001 Coating selection and application requirements for industrial plants and equipment (elaborated by Paints and Coatings Saudi Aramco Committee);
- AS/NZS 2312 Guide to the protection of structural steel against atmospheric corrosion by the use of protective coatings (elaborated by Standards Australia).

Although all the documents analyzed meet their objective, the quality and quantity of information regarding the whole process of protection of the metallic structures is substantially different.

There is a high discrepancy between the AR-82 recommendation drawn up by a non-specialized body in corrosion protection and the other documents drawn up by specialized bodies. Through the analysis
of table 3 where the main differences between the documents are presented, it is possible to comprehend that ISO 12944, the norm of Saudi Aramco and the Australian standard have common points, addressed with similar methodologies. The document drawn up by SSPC, despite its extent, has a lack of information regarding the abovementioned standards, which leads to difficulties in specifying a painting system. The greatest difficulty is the lack of indication of nominal dry film thickness and indicative durability.

As far as market adoption of these documents, manufacturers have indications regarding the application of their products for the protection of metal structures to corrosion. It is verified that manufacturers have more documents associated with the ISO 12944 Standard, demonstrating, in general, a greater acceptance and adoption in the market.

<table>
<thead>
<tr>
<th></th>
<th>AR 82</th>
<th>SSPC Manual</th>
<th>ISO 12944</th>
<th>SAES-H-001</th>
<th>AS/NZS 2132</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface preparation methods</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Good practices in the design phase</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Required level of surface preparation</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Corrosive environments classification</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Paint systems</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Specification of application methods</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Durability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

**Table 2 - Comparison between normative documents**

6 **Case studies**

The six study cases consist of different types of structures located in different environments. The subject of study was the intervention for conversion of a building to a hostel, the conversion of a building to a retirement home, the construction of an industrial building and three interventions for the preservation of bridges.

6.1 **Hostel**

This building dates to the first half of the 18th century, located in the historical area of Lisboa currently being converted into a hostel. The metallic elements used consisted of beams applied in the inside and outside environment for structural reinforcement.
The method used for surface preparation was manual sanding with no comparison to a pictorial guide. After that, it was used an alkyd urethane paint, with three coats for exterior elements and two coats for interior ones. There was no specification or measurement of the nominal dry film thickness of the applied coating.

Using the ISO 12944 standard, it is verified that the corrosive environments are C1 for interior elements and C3 for the exteriors. In this way, it is possible to conclude that for the exterior the expected durability will be less than five years since it resembles a 3.01 painting system. For the interior, since this is a C1 corrosivity zone, it is not considered necessary to apply paint for corrosion protection.

6.2 Industrial building

This pavilion consists of a framed metallic structure, which develops for approximately 62 meters, with spans of about 27 meters. It is located in Sintra, about seven kilometres from the coastal line.

The entire structure is in a heated interior environment, with no presence of condensation phenomena, corresponding to an exposure environment C1, according to ISO 12944-2. The specified painting system consists of the application of a coat and 80 µm of an epoxy primer two coats of 60 µm each of polyurethane hands. The paint system in the specifications is used for high durability in C3 exposure environments. It can be concluded that this protection system will have a high durability for the conditions envisaged and may be oversized for them.

6.3 Retirement home

This building dates from the 18th century, situated in Alcântara, Lisboa whose metallic elements to be applied consist of I-beams for reinforcement of floors and for the execution of the structure of stairs. All the elements are located indoors, however they have different corrosion environments: C1 for beams located in heated interior areas, C2 for metallic stairs and C3 for beams located in the food confection areas with high humidity production.

There is no paint system specification but there are some instructions in order to develop an anticorrosive protection solution: blast cleaning to Sa 2 ½ and application of a paint system suitable for a C3 corrosivity environment with high durability. The specification of the C3 corrosion environment for all metallic elements may lead to oversized painting systems for the environment in which they are located.

6.4 Bridges

The bridges that have undergone interventions are located in Abrantes, Gavião and Ourique. These structures consist of three bridges with mixed truss trays that are located in an environment with a corrosivity environment between C2 and C3.
For the structure located in Ourique, it was considered a corrosivity environment C3, surface preparation of Sa 2 ½ and the following paint system: a coat of a zinc rich epoxy primer with 80 µm; a coat of polyamide epoxy with 50 µm and two coats of polyurethane with 50 µm each.

The bridges located in Abrantes and Gavião were considered in a C4 corrosivity, surface preparation of Sa 2 ½ and the following paint system: a coat of a polyamide epoxy primer with 125 µm; a coat of polyamide epoxy with 125 µm and one coat of aliphatic polyurethane with 50 µm.

By comparison with the standard ISO 12944, the paint system used for the bridge in Ourique is similar to the S 3.19, concluding that the durability of the painting system is high. The paint systems used for the bridges of Abrantes and Gavião have a nominal dry film thickness equal to the system S 4.15. This solution corresponds to a high expectancy of durability so, it is expected the need for significant maintenance only after a period of more than 15 years. The choice of the corrosivity C4 environment for these bridges may result in oversized solutions with higher initial cost.

7 Conclusion

The analysis of the normative documents allowed to understand that the method for sizing a painting system goes, in the first place by the definition of the environment to which it is exposed and the durability intended. The most relevant document about anticorrosive paintings at national and European level is ISO 12944. This tendency is observed, for example, by the approaches of various brands present in the market explaining their methodology use. It is observed that the standard AS/NZS 2312 covers several themes, emerging as one of the most complete. This is due to its basis from ISO 12944 with modifications and updates.

The study cases analysed, despite their reduced number, allow to obtain conclusions. Of the six cases of study, three constituted works of a private nature and the remaining ones of a public nature. The private works consisted of protection of new structures, without any previously applied coating. The public works consisted in the maintenance of the metallic structure of works of art, including preparation of surface and application of a new coating. In this analysis, the lack of care was found in the specification of two painting systems and their lack, in design, of the anti-corrosion solution for one of the analysed structures. The anticorrosive paintings specified for the bridges were specified in accordance with NP EN ISO 12944, however, difficulties were felt in obtaining the required surface preparation level and in its verification in all elements of the structure. It is possible to recognize some tendency to neglect the durability issues during the project phase, especially in private-initiative works. This procedure can generate protection systems incorrectly and may lead to unexpected costs and incorrect maintenance plans.
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Standards:

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Websites:


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