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Corrosion protection of offshore wind farm structures – present understanding and future challenges

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Summary

Ensuring the highest possible quality of the protecting coating systems is a very important area with respect of limiting the lifetime cost of offshore wind farm projects. If early breakdown of the coating systems occurs on the offshore structures, costly and comprehensive repairs may become necessary.

Damage analyses and failure cases show that most defects occur due to faulty processing or wrong application. Many of the costly failures can thus be prevented by paying thorough attention to the complete painting process - going from the specification stage over the application process and to the final coating inspection.

1 Introduction

Corrosion protection of offshore wind farm structures is an area under tremendous development, since wind energy is widely recognised as a keystone in the future energy supply. In Europe and in other densely populated areas, public support for land-based wind farms is limited, which is why support for offshore wind farms is growing. Experience with offshore wind turbines and foundations dates back to the first offshore park, Vindeby in Denmark, built in 1991. At the beginning, the installation of offshore wind capacity was limited, but since the completion of Horns Rev 1 in 2002 in the Danish part of the North Sea, the development has accelerated. Currently, many offshore wind parks are under production and installation, particularly in Northern Europe, with even more parks on the drawing board.

However, the location offshore exposes the structures to heavy stresses and a severely corrosive environment. Coatings must withstand and protect against humidity with high salinity, reflecting UV light as well as tidal and wave action in order to protect the steel structures sufficiently. The offshore location furthermore entails that potential repair of the applied coating system due to defects or general climatic breakdown poses a challenge with repair costs of potentially more than 100 times, compared to similar jobs in onshore paint shops.

The paints and painting systems used for wind farm corrosion protection have developed during the last decades through – for instance - valuable experience gained from the offshore oil and gas industry. A combination of 2-3 epoxy coats and a polyurethane topcoat is often used; however the systems may vary depending on the exposure (atmospheric, immersed) and location. General recommendations for coating systems to be used offshore are given in international standards such as EN ISO 12944, ISO 20340 and NORSOK M 501.

It is essential that the application work is carried out in accordance with these international as well as the owner's specific standards, following the guidelines described in the paints' technical data sheets. If the paints are not applied correctly, and coating breakdown during service occurs, limited possibilities are available in order to repair the coating offshore - possibilities which are comprehensive and costly.

2 Protective coating systems currently used

The protective coating systems used for offshore wind structures must be divided into systems for atmospheric and immersed exposure, respectively.

2.1 Atmospheric exposure – steel towers

In general, the steel towers for wind turbines located offshore are metallised and painted on the outer surfaces. Inside the towers, both pure paint systems as well systems including metallisation may be used. According to *Mühlberg* [1] systems (1) and (2) below are often used.

System (1)

Metallisation (e.g. Zn/Al, 85/15)		60-100 µm
Epoxy paint	2x	100-120 µm (incl. flash coat)
Polyurethane paint		50-80 µm

System (2)

Epoxy zinc dust primer	60 µm
Epoxy mid coat	200 µm
Polyurethane top coat	60 µm

Today system (2) is more widely used due to the demands for less time spent on paint application. System (2) is also comparably less expensive.

2.2 Immersed exposure – foundation structures

The immersed foundation structures mainly cover the transition pieces (TPs) which are often placed on top of the monopole constructions (MPs). However, also structures such as jackets, tripods and tri-piles may be coated.

The foundation structures may be divided into permanently immersed areas as well as splash-zone areas. The permanently immersed areas may be coated by epoxy coating (2x 200-250 µm), however often the structures, such as the monopiles, will be left uncoated and instead protected by a cathodic protection system (e.g. by sacrificial anodes).

The TPs, which are situated in the splash zone, will often be coated by systems such as (3) or (4) [1]:

System (3)

Specialised epoxy coating	2-3x	200-250 µm
Polyurethane top coat		50-70 µm

System (4)

Specialised epoxy coating	2x	500 µm
Polyurethane top coat		50-70 µm

This application of at least three coats ensures a pore-free and dense protection which is protected from ingress of moisture and corrosive salts to the steel surface.

Depending on the design of the structures, all epoxy coatings for immersed exposure must be compatible with Impressed Current Cathodic Protection systems.

Inside the foundation structures, the areas that are not airtight and closed may be coated by epoxy coating (2x 200-250 µm). Also systems based on epoxy zinc dust primers may be applicable.

The inside areas of the foundations below the airtight platform are in general designed to be closed structures, which does not allow for exchange of air or seawater into the foundations. Hence the inside surfaces have in general been left uncoated, based on the assumption that the corrosion rates would be neglible (after all oxygen remaining from the installation works are consumed).

Recently, however, it has been widely discovered in the industry that exchange of both seawater and air may occur in the foundations resulting in more corrosion than expected on the inside surfaces [2]. Therefore, in future projects, more focus has been put on protecting the inside areas of the foundations. In some cases, 3-4 metres of the inside surface of the TP are coated in the area where the predominant water level is expected to be located (due to economical considerations as well as limited production time available).

3 Qualification of paint systems

General recommendations for coating systems to be used offshore are given in international standards such as EN ISO 12944, ISO 20340 and NORSOK M 501.

The standards prescribe that systems to be used offshore should be qualified by external testing according to:

- EN ISO 12944-6, corrosive categories C5-M and Im2 (both durability high, >15 years).

- ISO 20340, C5-Marine, Im2, tidal and splash zone and NORSOK M 510, coating systems 1 and 7.

4 Successful corrosion protection

The qualification of the systems does far from guarantee successful corrosion protection, since many other factors are decisive for the durability of the systems. Most defects, but not all, actually occur due to faulty processing or wrong application and not from incorrect specifications. Damage analyses in Germany have, reported by *Mühlberg* [1], shown that faulty processing and/or wrong application have caused between 43 % and 68 % of premature failures of the corrosion protection in the paint industry.

Consequently, it is essential to ensure that the surfaces to be protected are optimally prepared for coating application, including that the surfaces are accessible, meaning that the design considerations stated in EN ISO 12944-3 are complied with. Furthermore, the recommendations of ISO 8501-3 regarding preparation of welds and edges should be considered.

However, most importantly, it must be ensured that the application work is carried out in accordance with the international as well as the owner's specific standards, following the guidelines described in the paint's technical data sheet.

An optimal protection may furthermore be ensured by review of the painting facilities and procedure specifications for fabrication and control, scrutiny of the relevant quality documentation as well as control of procedures before, during and after paint application. In particular, checks of surface preparation, paint application and finish are crucial.

5 Failure cases

5.1 Specification flaw

On one of the first offshore wind farms, a one-coat system was being applied in two passes on the TPs instead of the mentioned 3-4 coat systems in (3) and (4). The coating itself was an above-average, highly resistant epoxy. But even though it was applied in two wet coats at the same time, eventually minute pores appeared in the protective film that allowed access of salts and water to the steel surface. The result was blisters created by osmotic forces, which resulted in spotted corrosion attacks after 2-3 years of operation, photo 1:

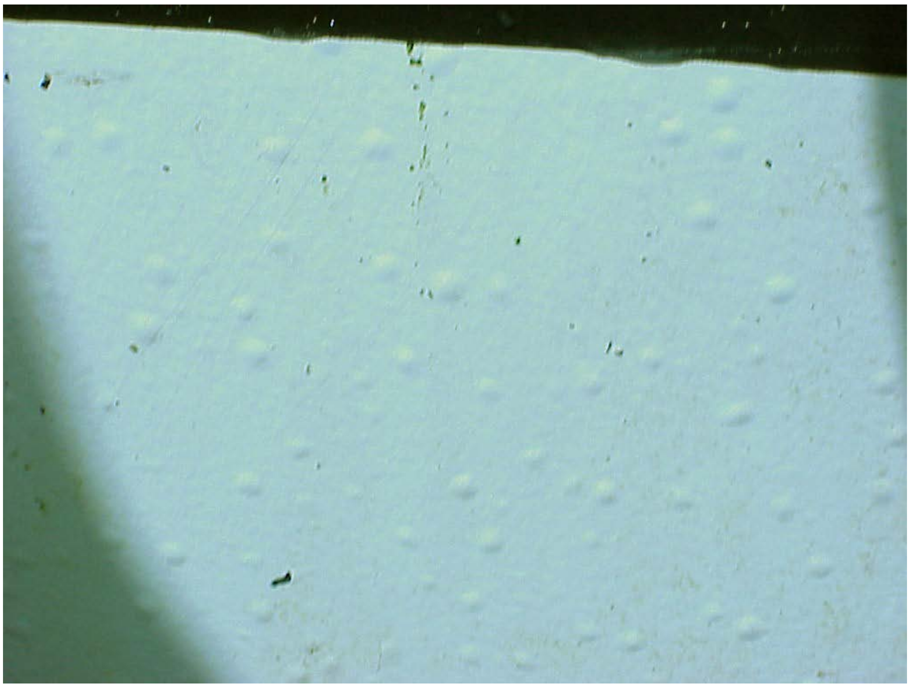

Photo 1
After 2-3 years of operation, parts of the surface of some TPs had blisters, sized 5-10 mm. Later, the blisters busted, and the steel surface became open to corrosion attacks.

As a test, five of the TPs in the same farm were applied at the same time with a system similar to (4). These five TPs stand out today as highly visible reminders of the benefits of the multiple coat application. Their spotless appearance in a farm covered with more or less rusty structures is certainly significant to any visitor.

5.2 Flaking of paint from galvanised steel surfaces

ISO 12944-2 tells that unprotected galvanising corrodes fast in marine surroundings (up to 8 µm a year). Accordingly, the newest specifications call for protection of the galvanised surface with a paint system. The combination of galvanising plus paint is also known as a Duplex system.

The Duplex systems are recognised as being highly protective in aggressive atmospheric conditions [3].

The secondary steel, i.e. railings, ladders, platforms, etc., on an offshore wind farm in the British Sector had been galvanised, painted and installed. Within a year, the coating system started to flake off, leaving the galvanising unprotected.

The reported flaking was not uniform: Most structures were unaffected, others had small flaked areas less than 100 cm^2, but on a few, large sheets of paint had come off.

Investigation revealed that preparation of the galvanised surface prior to application of the first coat had most probably been inadequate. The paint primer thus had insufficient anchor possibilities and detached.

If a galvanised construction is to be used in marine surroundings, the galvanising must always be abrasively swept with mineral abrasives to secure a sufficiently abraded surface for the paint to adhere to.

An applicator's blunder followed by insufficient surface inspection has thus resulted in spotted structures.

5.3 Flaking from the prime coats

On an offshore windfarm, the top coat and its underlying primer detached in areas around the boatlanding. The structure had been painted with system (3), and the flaking thus took place between the second and the third coat of primer. However, the fault did only occur in or close to areas where the supply boats hit the boatlandings during off- and onloading, photo 2, or near the flanges of the TPs. The coats were firmly adhering in all other areas.

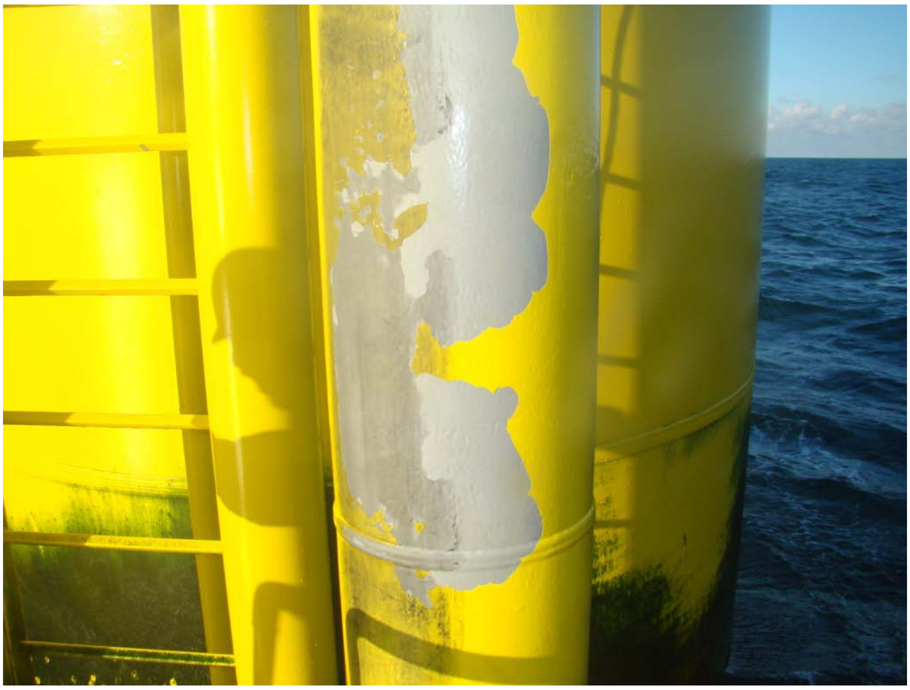

Photo 2
Flaking of top coats from a boatlanding due to root cause (b) described below. The light grey parts had been opened just before the photo was taken. The darker grey areas were from earlier operations.

The number of TPs with these faults was approximately 10 % of the total number of turbines.

After a detailed root cause investigation, which included chemical analyses of the underside of detached paint flakes and examination of daily logs from the painting operations, two independent causes, (a) and (b), of the fault were identified:

a. The chemical analyses showed surprisingly high amounts of aluminium and zinc on the backside of the flake. As the underside of the TP flanges had been thermally sprayed (metallised) it was assumed that part of the boat landings had not been covered sufficiently during the metallising process. Sprayed metal dust had thus settled on the primed surface and not been removed prior to finishing.

b. Painting operation records showed that, due to stops in the production, the faulty TPs with the mounted boat landings facing upwards had been stored partly painted in a horizontal position and outdoors for more than a month during hot summer periods. As the boat landings were positioned horizontally, their upper side faced the sun. When exposed to UV-light, the epoxy primers started to chalk and after months of hot exposure, their maximum recoat interval was surpassed. Thus, when they were overcoated, their surface was not somewhat sticky but instead chalky and very hard. An applied new coat did not adhere sufficiently to such a surface.

5.4. Too high dry film thickness (DFT)

Epoxy paints, and in particular solvent-containing epoxy paints, have an upper critical application limit. If they are applied in coating thicknesses above their maximum limit, the coating may develop inner stress inside the coating film. The paint film may also entrap solvents because the evaporation of the solvents is hindered when the thick paint film cures to a solid coating.

In both cases, the physical properties of the coating film will be below standard. During service, and when exposed to climatic and physical impacts the film cracks and corrosion attacks follow, photo 3:

Photo 3
Cracks created by inner tension in the coating film give access to corrosion attacks.

To prevent this, a careful application is recommended with repetitive control of both the wet and dry film thicknesses during the process.

6 Repair of coating failures offshore

The most important factor in any offshore paint repair process is the weather. The sea has to be calm, and wave action as small as possible for easier logistics. Additionally, rainy weather must be avoided – unless the area to be prepared and painted is covered. There are also environmental restrictions on the debris from e.g. blasting. It must be collected and delivered to depots onshore.

Often if platforms, ladders or boatlandings are to be repainted, they may beneficially be taken to proper painting shops on land and then reinstalled after painting, leaving only consoles or clamps to be painted offshore.

For the repair, surface tolerant solvent-free epoxy’s are recommended.

For the immersed surfaces, repair is not possible. However, in these areas, the cathodic protecting system by sacrificial anodes protects any exposed steel area. Therefore, if damage to the coating below the waterline is observed, the efficiency of the cathodic protection should be determined, if not already checked.

Painting the outside of installed TPs is a challenge due to tidal surroundings and the above-mentioned weather conditions. Two methods appear feasible:

Roping
The painters are clamped to and work from cross-mounted ropes moving around like spiders in a net. The ropes are fastened to the surface of the TP by magnets.

Scaffolding
Scaffolds that follow part of the perimeter of the TP are fastened by clamps to the underside of the platform and to the TP sides by magnets. Thereby the painters can operate and walk freely. The scaffolds can even be covered by tarpaulins, which allows for less dependency of the weather.

Painting the inside areas of installed TPs is an area not yet conducted. However due to the recent discoveries of more than expected corrosion inside the foundations, coating of areas internally may become applicable. The potential work inside the foundations however requires compliance with working in confined spaces and entails large logistical challenges.

7 Outlook

The overall objective of the whole enterprise of painting is to obtain offshore wind farms without need of costly and premature repair operations. Accordingly, all costly failures listed above can be prevented by paying thorough attention to the complete painting process - going from the specification stage over the application process and to the final coating inspection. Meticulous documentation covering both the contract specifications, daily logs, inspection forms and more also has a preventive effect on possible faults.

Since the cost of offshore coating maintenance is 10 - 100 times as high as the maintenance cost on land, the cost of the original complete coating operation may be insignificant, once premature offshore maintenance becomes relevant. In this respect, it must be recommended that paint professionals and certified inspectors (NACE or FROSIO) inspect all steps of the protective coating process during construction.

8 References

[1] Karsten Mühlberg, Hempel (Germany) Ltd, Pinneberg, Germany: *Corrosion Protection of Offshore Wind Turbines – A Challenge for the Steel Builder and Paint Applicator*, PCE October-December 2009.

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[3] J F H van Eijnsbergen: *Duplex Systems.* Hot-dip Galvanizing Plus Painting, Amsterdam, 1994.