CORROSION PROTECTION OF OFFSHORE WIND TURBINES

A Challenge for the Steel Builder and Paint Applicator

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Standards for Corrosion Protection Offshore
Protective Coating Systems Currently Used by the Offshore Wind Energy Industry
Qualification of Paint Systems
What Is Decisive for Successful Corrosion Protection?
Surface Preparation and Paint Application
The Coating System
Conclusion
References
Corrosion protection is always the last step during a production process. When a job is behind schedule, there is often pressure on the paint shop to make up for lost time by hastening its part of the production process. Trying to solve these time-related problems by compromising the painting process, however, can create an extremely costly situation. The cost of painting offshore structures in a paint shop is 15 to 25 €/m² (depending on the setup of the workshop and the paint system). The cost of coating work performed on site, onshore (e.g., at a construction site) is approximately 5 to 10 times more. But, if due to premature failure of the corrosion protection, repair work must be done offshore, the cost can increase to more than 1,000 €/m², more than 100 times the cost of doing the job in the paint shop (with all job-related costs accumulated). The moral here is: Whatever your time problems may be, do not place them on the paint shop! Painting offshore is more expensive than painting onshore due to several factors, including the logistics of getting men and materials to the job site and the limited access to the structures created by offshore weather conditions. Correctly specifying and applying the protection system is important because the exposure environment is very severe. The main differences between onshore and offshore exposures are summarized below.

• Onshore—generally cyclic dew/condensation with or without minor salinity and moderate exposure to sunlight, resulting in moderate corrosion at holidays, weak points, and damaged areas of the coating system
• Offshore—long-term exposure to humidity with high salinity, intensive influence of UV light, wave action, and the presence of a splash zone area, and high corrosive stress give rise to dramatic, very fast corrosion at holidays, weak points, and damaged areas of the coating system.

This difference in exposure severity is also reflected in the mass and thickness loss per unit surface of low-carbon steel and zinc in the first year of their unprotected exposure. For example, in Germany, the onshore corrosivity is evaluated as being about C3, according to ISO 12944 (Table 1). In addition, for splash zone areas, up to 500 μm1 thickness loss has been observed in the first year of service. You cannot, therefore, pay enough attention to the process of corrosion protection of offshore structures. The design and fabrication of steel used in wind turbine construction are also critical aspects of the corrosion protection of the steel. This article will discuss the various paint systems used on offshore wind turbines and also give guidance on minimizing potential problems related to the design and fabrication of the structure.

Standards for Corrosion Protection Offshore

Today, corrosion protection of offshore structures in Europe is regulated mainly by the following standards.
• DIN EN ISO 12944: Corrosion protection of steel structures by protective paint systems
• ISO 20340: Paints and varnishes – Performance requirements for protective paint systems for offshore and related structures
• NORSOK M 501: Surface preparation and protective coating

Some companies, especially those in the gas and oil industry (Shell, BP, Total, Texaco, etc.), also have their own standards. A selection of the recommendations of the above mentioned standards for painting carbon steel are summarized in Tables 2 and 3. In addition, further recommendations are mentioned in the company standards for painting hot-dip galvanized and metallized surfaces.

Protective Coating Systems Currently Used by the Offshore Wind Energy Industry

Since 1991, starting with the offshore wind park Vindeby, more than 20 offshore wind projects have been installed and successfully painted in Europe. The paint systems most commonly used to protect the various areas of these structures are described below.
Exterior Atmospheric Corrosion Protection

The majority of steel towers for wind turbines located offshore are metallized and painted on their outer surfaces. Inside the towers, only pure paint systems are typically used, except for the lower part where some specifications call for metallization plus paint.

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

However, due to the demands for less time spent on painting, cost reduction, and good experience over years with paint systems, wind turbine structures may be metallized less often. More and more, high quality paint systems without metallizing (according to DIN EN ISO 12944, C5-Marine), at 320 μm dry film thickness (dft) for external protection, are going to be used. An example of such a paint system is an epoxy zinc dust primer applied at 60 μm dft; an epoxy midcoat at 200 μm; and a polyurethane topcoat at 60 μm.

Inside of steel towers, paint systems at 240 μm dft (C4) are going to be used. For example: epoxy zinc dust primer at 60 μm; epoxy paint at 180 μm; and another coating system used: epoxy zinc dust primer at 60 μm; epoxy midcoat at 120 μm; and a polyurethane topcoat at 60 μm.

Notes for Tables 2 and 3

- EP–Epoxy resin
- PUR–Polyurethane resin
- Zinc rich–Zinc-rich primer as defined in ISO 12944-5:2007, Sub clause 5.2 (minimum 80% by mass of zinc dust in the non-volatile part of the paint). The zinc dust pigment shall conform to ISO 3549
- C5-Marine, Im2 high–Corrosivity categories according to ISO 12944, high: time period until first maintenance, more than 15 years.

Table 1: Severity of Corrosion According to Corrosivity Category

<table>
<thead>
<tr>
<th>Corrosivity category acc. to DIN EN ISO 12944</th>
<th>Mass/Thickness loss in the first year</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONSHORE, e.g. C3, urban and industrial atmospher-</td>
<td>200-400 g/m²</td>
</tr>
<tr>
<td>pheres, coastal areas with low salinity. Typical location for an onshore wind turbine.</td>
<td>25-50 μm</td>
</tr>
<tr>
<td>OFFSHORE, C5-Marine, coastal, and offshore areas with high salinity.</td>
<td>650-1500 g/m²</td>
</tr>
<tr>
<td></td>
<td>80-200 μm</td>
</tr>
</tbody>
</table>

Table 2: Atmospheric Exposure

<table>
<thead>
<tr>
<th>Norm/Standard</th>
<th>Prime coat</th>
<th>Number of layers</th>
<th>Total dry film thickness in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIN EN ISO 12944 C5-Marine, high</td>
<td>EP, PUR EP, PUR EP, PUR (zinc rich)</td>
<td>3-5 2 4-6</td>
<td>320 500 320</td>
</tr>
<tr>
<td>ISO 20340, C5-Marine, high</td>
<td>EP (zinc rich) EP</td>
<td>min. 3 min. 3</td>
<td>&gt;280 &gt;350</td>
</tr>
<tr>
<td>NORSOK M 501</td>
<td>EP (zinc rich) EP</td>
<td>min. 3 min. 2</td>
<td>&gt;280 &gt;1000</td>
</tr>
</tbody>
</table>

Table 3: Under Water and Splash Zone Areas

<table>
<thead>
<tr>
<th>Norm/Standard</th>
<th>Prime coat</th>
<th>Number of layers</th>
<th>Total dry film thickness in μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIN EN ISO 12944 Im2, high, splash zone not described</td>
<td>EP (zinc rich) EP</td>
<td>3-5 1</td>
<td>540 600 800</td>
</tr>
<tr>
<td>ISO 20340, Im2, high, splash zone</td>
<td>EP, PUR (zinc rich) EP, PUR EP</td>
<td>min. 3 min. 3 min. 2</td>
<td>&gt;450 &gt;450 &gt;600</td>
</tr>
<tr>
<td>NORSOK M 501</td>
<td>EP</td>
<td>min. 2</td>
<td>min. 350*</td>
</tr>
</tbody>
</table>

* The coating system shall always be used in combination with cathodic protection.

Immersion and Splash Zone Corrosion Protection

Up until now, the foundation structures of wind turbines have mainly been monopile construction, although jackets, tripods, and tri-piles have also been used for construction. The following coating systems have most commonly been used on such windfarms as Kentish Flat, Egmond aan Zee, Barrow, Q7, Fino III, Fino 3, Alpha Ventus, and Bard Offshore I.

- For external (immersion and splash zone) use: specialized epoxy coating, 2 to 3 coats, each at 200–250 μm*; polyurethane topcoat at 50–70 μm; specialized epoxy coating, 2 coats at 500 μm*; and polyurethane topcoat 50–70 μm.
- For permanently immersed areas: Epoxy coating, 2 coats at 200–250 μm*
- * The epoxy and specialized epoxy coatings above, depending on the design of the relevant structure, must be compatible with Impressed Current Cathodic Protection.
- For foundation structures insides (not air tight closed): epoxy coating, 2 coats, each at 200–250 μm are normally used.
Qualification of Paint Systems

Paint systems to be used for offshore corrosion protection should be qualified by external testing according to the following.

- EN ISO 12944, part 6, Corrosivity categories C5-Marine and Im2 (durability high, > 15 years)
- ISO 20340, C5-Marine, Im2, tidal and splash zone and NORSOK M 501, coating systems 1 and 7

The tests include the exposure of painted test panels to over 4,200 hours of different stresses such as UV–light, condensation, salt spray, and freezing (Fig. 1). Further tests include immersion in seawater (ISO 2812-2) and cathodic disbonding (ISO 15711:2003, method A), also for a time period of 4,200 hours.

What Is Decisive for Successful Corrosion Protection?

Is a qualified coating system a guarantee for successful corrosion protection? The answer is short and simple: NO.

Certificates and approvals are often overestimated. Why? The EN ISO 12944, part 5 (German issue) lists 9 factors that are decisive for the durability of a coating system. The coating system itself is only one of them. The most important factors are:

- design of the structure, access possibilities;
- design of edges and weld seams;
- workmanship of the applicator;
- condition of the steel before surface preparation; and
- exposure of the paint system immediately after completing application.

This is also reflected in the failure statistics shown in Tables 3 and 4. As seen in Tables 4 and 5, the paint system itself is very seldom the reason for premature failure of the corrosion protection. That is because the paint industry is mainly supplying “half-products,” i.e., two or more component reactive resins. It is the applicator who, by doing his job, creates a chemically new substance that in the end provides the corrosion protection. Failure can occur during this process if correct mixing of the components, at the right temperature, in the right time, and the correct application of the mixture onto correctly prepared surfaces are not carried out. That is also why permanent quality control and supervision by qualified people is of utmost importance.

But before the applicator starts his job, the steel builder has to provide a structure that is suited to be painted successfully. It is like a law of nature that corrosion will always start at edges and weld seams—and this is where the responsibility of the steel builder begins. Some decisive and key points are discussed below.

Design Considerations

Coatings can protect only accessible surfaces. This fact is often neglected in design. EN ISO 12944, part 3, Design Considerations, includes the following recommendations.

- Annex A: Typical distances required for tools in corrosion protection work
- Annex B: Recommended minimum dimensions of openings for access to confined areas
- Annex C: Minimum dimensions for narrow spaces between surfaces

Table 4: Damage Analysis of 120 Cases

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Faulty coating material</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Wrong specification</td>
<td>19%</td>
<td>41%</td>
</tr>
<tr>
<td>Changes environmental conditions</td>
<td>11%</td>
<td>11%</td>
</tr>
<tr>
<td>Faulty processing/ wrong application</td>
<td>68%</td>
<td>48%</td>
</tr>
</tbody>
</table>

Table 5: Damage Analysis, Hydraulic Steel Works, Germany

<table>
<thead>
<tr>
<th></th>
<th>1990 – 2000 with ISO 9000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faulty processing/wrong application</td>
<td>43%</td>
</tr>
<tr>
<td>Planning</td>
<td>14%</td>
</tr>
<tr>
<td>Galvanic Elements</td>
<td>20%</td>
</tr>
<tr>
<td>Microbiological Reasons</td>
<td>7%</td>
</tr>
<tr>
<td>Various</td>
<td>16%</td>
</tr>
</tbody>
</table>

Fig. 2: Areas difficult to paint thoroughly Photos on pgs. 23-32 courtesy of the author.

Fig. 4: Poor edge/weld finishes
Construction designs that create insufficient access for painting, such as those shown in the photographs in Fig. 2, should be avoided.

During the fabrication of an offshore steel structure, the recommendations of ISO 8501, part 3 (preparation grades of welds, edges, and other areas with surface imperfections) should also be considered. The content of this relatively new standard first addresses the steel builder, not the painter. In writing and with pictures, it gives recommendations about how the condition of the steel surface has to be if paints have to be applied later on for long-term corrosion protection.

This standard does not appear to be well known at engineering offices and steel construction companies. Examples from this standard are given in Fig. 3.

For offshore structures, preparation grades P2 or P3 should be specified, depending on the relevant details of the structure.

Steel surfaces such as those shown in Fig. 4 should be avoided, or they will have to be corrected. Weld spatters must be removed completely; laminations, sharp edges, and thermally cut edges must also be removed by grinding (min. 2mm radius). This should mainly be done by the steel builder!

Pores are often found, particularly on welds (Fig. 5), and inspectors are often asked if pores can be filled up with paint. Pores should never be filled with paint or filler. The steel builder has to repair them, according to the demands of EN ISO 5813, weld quality B. Some of the pictures in Fig. 5 even show the first signs of corrosion in the pores.

The correct design of weld seam is extremely important for successful corrosion protection. In general, handmade weld seams on offshore structures generally always need to be ground before they can be painted successfully. Again, the steel builder is responsible. Figure 6 shows examples of unacceptable weld seams.

Poor weld seam design will cause steel to corrode quickly. The photographs in Fig. 7, taken from offshore structures, show the weld seams exposed to the sea only for some weeks or months. Insufficient application of the paint system (no stripe coating) was also reason for this premature failure.

It is often helpful to have something to show to the welder to clarify what is meant by the right design for corrosion protection of a weld seam. The NACE Standard RP 0178 (Fabrication Details, Surface Finish Requirements and Proper Design Considerations for Tanks and Vessels to be Lined for Immersion Service, Visual Comparator- Surface Finishing of Welds), for example,
can be used for this. RP 0178 gives photographic examples of the front and back sides of good and bad weld seams. And last but not least, the steel builder has to be careful about the condition of the carbon steel to be used to build an offshore structure. Unpainted steel is characterized by four rust grades according to EN ISO 8501, part 1. For offshore structures, it is strongly recommended to use steel with a rust grade not worse than B (Norsok M501), or not worse than C (EN ISO 12944). As can be seen in Fig. 8, the service life of a coating system (in years) depends on the rust grade of the initial steel and the degree of surface preparation (Sa2 and Sa3 according to EN ISO 8501, part 1).

In summary: The steel builder has to be aware that he is constructing an offshore structure that needs certain access and surface conditions for successful corrosion protection. The builder is the first of many tradespersons to share in this responsibility.

Surface Preparation and Paint Application

The workmanship of the applicator is very important for the long service life of a coating system. High quality during all operations and frequent quality control checks are the key factors. Remember, about half of all premature corrosion protection failures are application-related. Correct surface preparation and coating thickness are definitely the most important application actors. Documentating the different working steps and, preferably, signing off on the results of the work are necessary to perform quality work. Because offshore structures present some of the toughest corrosion protection challenges for coating systems, the best possible equipment and set up should be always be used for the painting job. Automatic blast facilities should be used to minimize variations in surface cleanliness and surface roughness. Painting booths with climate control and temperature regulation are recommended, two-component spray equipment should be used to minimize mixing errors, and qualified people should be hired for the job. The foreman and/or the supervisor, at least, should be qualified and certified according to FROSIO or NACE level 3 or equivalent. Figure 9 shows examples of highly sophisticated blasting and painting set ups. Although these are not standard everywhere, the aim should be to come as close as possible to such modern working conditions.

The Coating System

Today more than ever, the market for corrosion protection of steel wind towers is marked by strong competition. Coating application around the clock, 24 hours every day, under time pressure, carried out by foreign laborers with whom communication is often very difficult, are typical aspects of a day of coating work. The demand increases for faster drying coatings, lower thicknesses, and fewer coats.

Another critical point is this: Customers often consider successfully passed tests and coating systems certificates as guarantees of successful coating performance. Does this make sense in every case? The answer is a clear NO.

Today, it is possible to qualify, to the highest requirements, one- and two-coat systems applied at film thicknesses less than mentioned previously in this article.

It is one thing to apply the very best coating under laboratory conditions onto perfectly prepared test panels and submit the panels to laboratory testing. But it is a completely different matter to reproduce these same results on site — on thousands of square meters of steel, applied around the clock and sometimes under less than optimal conditions. The more difficult a coating system is to apply, the higher the requirements during application. Therefore, the applicator is more responsible than the paint supplier for the success of a coating application. This should be absolutely clear.

ISO 20340, Performance requirements for protective paint systems for offshore and related structures, points out "...experience has shown that one of the parameters which is essential for the achievement of high durability in practice is the coating system makeup, primarily the number of coats and the total dry film thickness...

The point to note is "...experience has shown..." not testing in a laboratory. Experience has shown, for example, that it is more reliable and safe to apply a coating system in three coats of 200 μm dft instead of two coats at 300 μm. And if a two-coat system is preferred, apply two coats at 500 μm. Do not apply the coatings at the absolute minimum dft requirements; consider safety margins. That is the message.

Coating materials should therefore not only be easy to apply, but also be versatile and able, to some extent, to tolerate variations in application that occur in daily practice. Nothing reveals more about the quality and performance of a coating system than practice references and case histories, preferably in the offshore industry. Case histories tell you much more than any tests ever can. They indicate if the coating system is performing well in practice, in the field, and if it can be
• reliably applied daily at different locations by poorly trained people;
• reliably applied at different temperatures, during all seasons;
• reliably applied onto different structures, onto complicated geometry, with low spray dust pick up, good flow properties, good sag resistance, and good thickness tolerances; and
• reliably repaired on site by different people using standard methods.

Case histories can also reveal if a paint supplier company has the right philosophy and the right attitude in going offshore with its coating solutions. Long-term experience with a company is the most reliable basis for coating selection, even if new, unproven coating systems will be required.

The steel builder, paint applicator, and paint supplier are all responsible for the success of the corrosion protection of wind turbines. They must work closely together to achieve the best results.

Conclusion

References


After studying Chemistry at the University of Leipzig, Karsten Mühlig worked for Lacufa, a former East German paint manufacturer. In 1992, he joined Germany-based Hempel. He is currently responsible for Hempel’s technical service department.