Investigating Corrosion Protection of Offshore Wind Towers

Part 1: Background and Test Program

Andreas W. Momber, Muehlhan AG,
Hamburg, Germany;
Peter Plagemann, Volkmar Stenzel;
Fraunhofer Institute for Manufacturing
and Applied Materials Research,
Bremen, Germany; and
Michael Schneider, Fraunhofer Institute
for Ceramic Technologies and Systems,
Dresden, Germany

The installation of offshore wind energy mills in both the North Sea and the Baltic Sea is one of the most recent approaches for alternative production of energy. A number of offshore wind energy parks have already been established in these areas, and others are under consideration. An offshore wind energy mill basically consists of a foundation, the actual tower, and the turbine rotor construction (Fig. 1).

The tower is usually mounted on the foundation by a bolted flange. This article deals with the corrosion protection of the towers and part of the foundation. These towers are ambitious engineering constructions. They can be as high as 80 meters for offshore installation; the diameter can be as large as 7 meters; and the wall thickness can be in the range of several centimeters (Fig. 2).

Offshore wind energy towers are exposed to harsh and complex stresses, including the following:
- corrosive stress,
- physical load, and
- biological stress.

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Burbo Bank Offshore Wind Farm (Liverpool Bay)
Courtesy of Siemens Wind Power

This article deals mainly with the corrosive stress, although researchers found that biological stress may also play a role in the conditions offshore. The corrosive stress includes features such as seawater exposure, wet-dry cycles, temperature variations, construction details (joints, bolts, welds), and construction materials (material combinations).

The location of steel structures several miles offshore is not a new situation. Oil and gas exploration and extraction platforms have performed in such areas for decades. The coating industry has, over the years, developed special coating systems, to protect offshore structures from corrosion. A simple approach for protecting offshore wind energy towers could be to adapt coating systems for offshore platforms to the wind towers. This approach would also allow for the use of standard assessment schemes developed by the industry and regulatory bodies.[1,2] There are, however, critical differences between platforms and towers, the most significant being that offshore wind energy towers are unmanned structures with highly restricted access. On oil and gas platforms, corrosion protection systems are generally under permanent inspection, which is not the case on offshore wind energy towers. Thus, whereas on oil and gas platforms, areas of deteriorated coating can be recognised and repaired comparatively easily, such repairs are not feasible on offshore wind energy towers.

In this article, the authors discuss a nationally funded project on the performance testing of different corrosion protection methods under site and laboratory conditions. This first part deals with the rationale behind, and the setting-up of, the test program. A second article will discuss the test results.

Corrosive Stress and Corrosivity Category

Corrosive stress depends largely on the location of a structure. An offshore wind energy tower, as a sea-based construction, has significant exposure in several zones, including the following:[2,3]

- underwater zone (UZ), the area permanently exposed to water;
- intermediate zone (IZ), the area where the water level changes due to natural or artificial effects, and the combined impact of water and atmosphere increase corrosion;
- splash zone (SZ), the area wetted by wave and spray action, which can cause exceptionally high corrosion stresses, especially with seawater.

The environmental zones above can be classified as per Fig. 1. Corrosion zones considered in this study are marked. The corrosion rate of steel in these environments can be greater than 2.5 mm per year.[4] It is already known that corrosion rates of steel are highest in the splash zone.[4] Table 1 lists results reported in reference 4. In Table 1, the splash zone, which features the flange connection between foundation and tower, seems to require particular attention for corrosion protection. However, using the values in Table 1 requires caution, because they are based on the corrosion of unprotected steel, whereas the present investigation deals with the performance of protective coating systems over steel.

Two corrosivity categories must be considered for offshore wind energy mills:[3]

- C5-M: very high, marine; coastal and offshore areas with high salinity, and
- Im2: seawater or brackish water (including offshore structures).

Selection of Corrosion Protection

Systems for Wind Energy Towers

The specification for a corrosion protection system for wind energy towers should address the following demands:

- high corrosive stress due to elevated salt concentration in both water and air,
- mechanical load due to ice drift or floating objects,
- biological stress, namely under water,
- notable variations in temperature of both water and air,

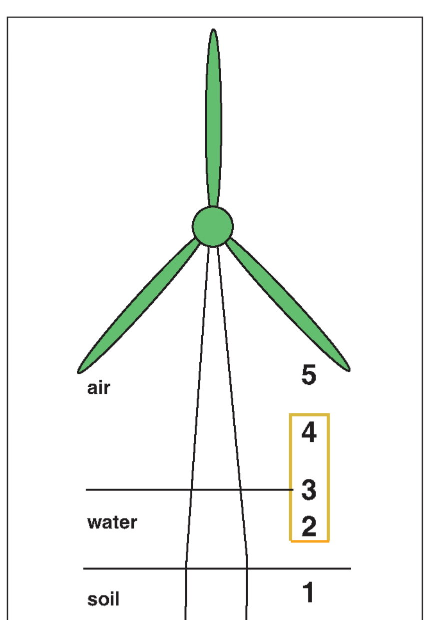


Fig. 1 (Left): Corrosion zones on offshore wind energy towers. 1= buried in soil; 2 = underwater zone (UZ); 3 = intermediate zone (IZ); 4 = splash zone (SZ); 5 = atmospheric zone
Courtesy of the authors

Table 1: Corrosion Rates of Steel in Offshore Service[4]

Environmental zone	Corrosion rate (mm/year)
Buried in soil	0.1
Underwater zone (UZ)	0.2
Intermediate zone (IZ)	0.25
Splash zone (SZ)	0.4

• long and irregular inspection intervals because of reduced accessibility, and
• high maintenance and repair costs in case of coating failure.

The formal way to select a system is to consider the corrosivity categories according to reference 3. If the categories are combined with a given durability range, general coating system schemes can be pre-selected.[5] The general scheme covers the following coating parameters: binder, primer type, number of coats, and nominal dry film thickness. A typical system that meets the corrosivity categories C5-M and Im2 would include a zinc-rich, epoxy-based priming coat (60 µm); three subsequent epoxy midcoats, and one polyurethane topcoat, with a total nominal dry film thickness of 400 µm. However, this selection process considers only organic coating systems, not the detailed application of metal coatings, which are quite common on wind energy towers. Coating systems, typically applied to traditional offshore structures, are specified in reference 2, where hot-dip galvanised and metallized steel substrates are included.

Reference 6 reviews coating systems applied to offshore wind energy towers in the past. The systems basically consisted of a Zn/Al-metallization, organic pore filler, several intermediate epoxy-based coats and a polyurethane-based topcoat. A typical total dry film thickness was about 400 µm. Reference 7 describes a coating system on offshore wind energy towers that provides high abrasion resistance.

Table 2: Qualification Tests for Offshore Coating Systems (ISO 20340)

Test	Artificial scribe	Testing duration for Im2		
		SZ	IZ	UZ
Ageing resistance*	Yes	4,200 h	4,200 h	-
Cathodic disbondment	ISO 15711	-	6 months	6 months
Seawater immersion (ISO 2812-2)	Yes	-	4,200 h	4,200 h

*See written text, pp. 34-35.

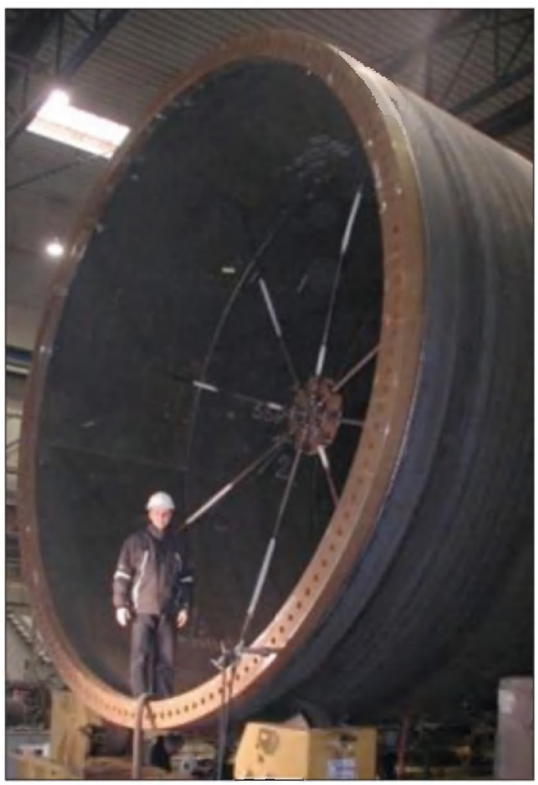


Fig. 2: Dimension of a typical wind tower construction
Courtesy of Muehlhan A/S, Vissenbjerg

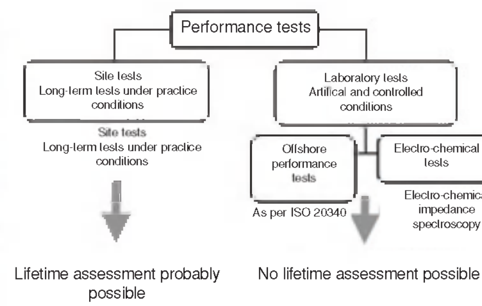


Fig. 3 (Above): Summary of performance tests
Courtesy of the authors

Test Procedures

Testing and assessment methods for corrosion protection systems may be subdivided into laboratory tests under defined artificial stress conditions and site tests under real stress conditions. Figure 3 summarizes all tests for the present study.

The site tests included long-term exposure tests in a real corrosion environment. They were performed at the seawater test site at the island of Helgoland, 70 km off the German coast. The test site featured three galleries: one for the underwater zone (UZ) environment; one for the intermediate zone (IZ) environment; and one

Table 3: Parameters of the Cathodic Disbonding Tests

Parameter	Test A, based on (9)	Test B, based on (8)
Exposure time	30 days	180 days
Applied cathodic potential	-1,450 mV_{SCE}	-1,050 mV_{SCE}
Electrolyte	Potable water; added: 10 g/l sodium chloride 10 g/l sodium sulphate 10 g/l sodium carbonate	Demineralized water; added: 23.8 g/l sodium chloride 9.8 g/l magnesium chloride 8.9 g/l sodium sulfate 1.2 g/l calcium chloride

Fig. 4 (Left): Outdoor test stand at Heigoland with specimens. Courtesy of the authors

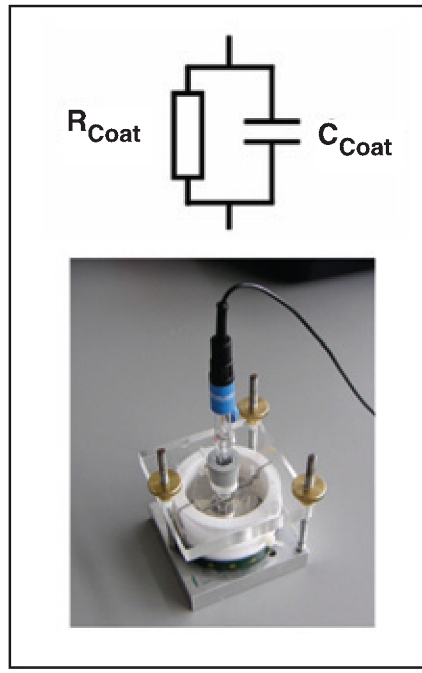
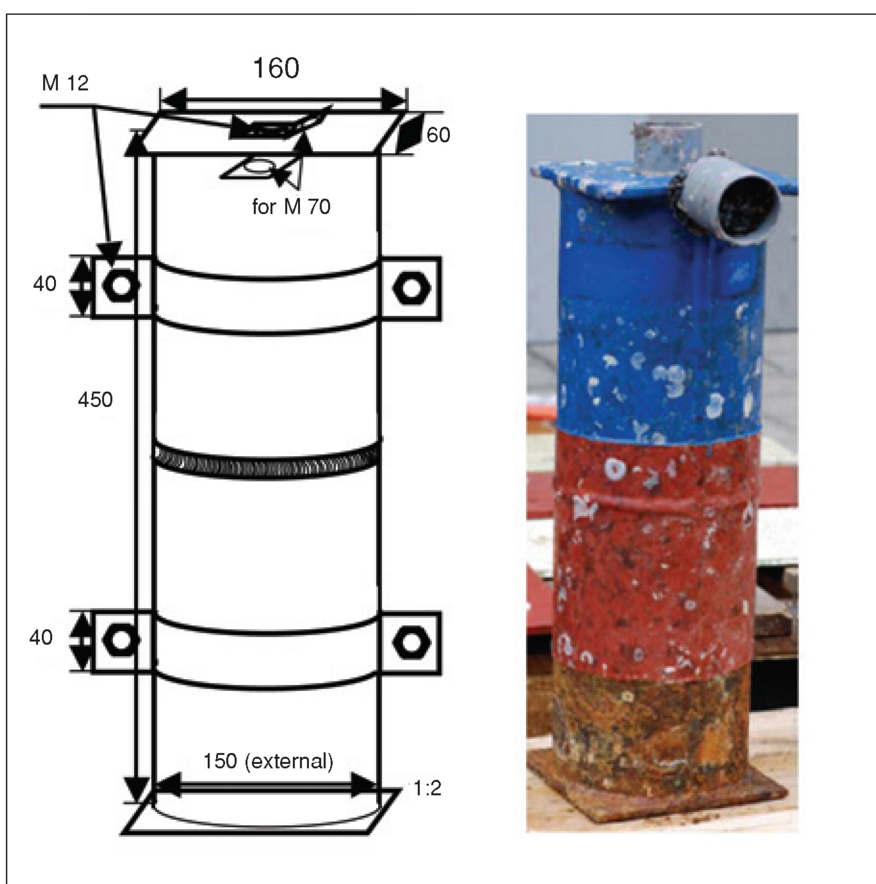


Fig. 5 (Left): Set-up for electrochemical impedance spectroscopy measurements, and equivalent circuit
Courtesy of the authors

Fig. 6 (Below): Specimen design for underwater zone (UZ); dimensions in mm
Courtesy of the authors



for the splash zone (SZ) environment. Figure 4 shows the test site, where the specimens for the SZ and the IZ can be recognized. The specimens for UZ, which are submerged, can be seen as discoloration of the water surface. All specimens were tested for three years. Part of the site test procedure was cathodic protection, consisting of an impressed current system. The applied potential was controlled to -880 $mV_{Ag/AgCl}$.

The laboratory tests were subdivided into ageing tests according to ISO 20340,[2] cathodic disbonding tests,[8,9] and tests based on electrochemical impedance spectroscopy (EIS). All tests were performed in the laboratory at IFAM, Bremen. The procedure prescribed in reference 2 includes a combination of UV/condensation, salt spray, and low-temperature exposure cycles. The exposure cycle in the procedure lasts a week (168 hours) and includes the following stresses (see also Table 2):

• 72 hours (3 days) of exposure to UV (UV [B] lamps) and water,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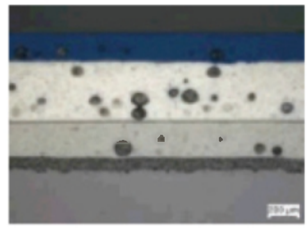
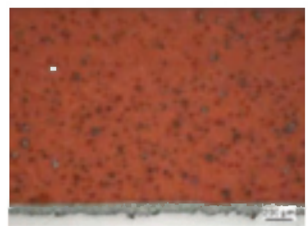
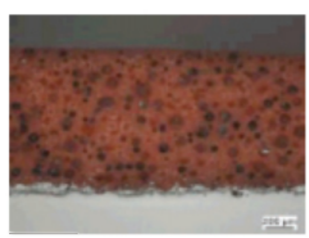
• 72 hours (3 days) of exposure to salt spray, and
• 24 hours (1 day) of exposure to low temperature (-20 C ± 2 C).

A total of 25 cycles (25 weeks) were run. Part of the assessment procedure was cathodic disbonding according to references 8 and 9. For these tests, specimens with the design shown in Fig. 10 (p. 49) were used. Holes were drilled through the coating down to the substrate, and the samples were exposed to synthetic seawater. Table 3 lists details on the test parameters.

However, these tests are plain pass/fail tests. Although they allow for a comparative evaluation of different paint systems, they do not provide information on the paint degradation processes or on corrosion progress. A promising method for gathering degradation and corrosion information on coatings for wind energy towers is EIS.[10,11] Therefore, additional EIS tests were performed on a number of laboratory samples. EIS was carried out on coated steel specimens, which had been stored in a 3% NaCl solution for up to 62 days. The measurements were performed according to the three-electrode-method with an onset cell of 8 cm diameter. The testing device is shown in Fig. 5. The spectra were measured from 100 kHz to 0.01 Hz; with a potential amplitude of 20 $mV_{Ag/AgCl}$. From the obtained spectra, barrier resistances were determined by fitting a simple RC (ohmic resistance/capacitor) equivalent circuit (Fig. 5).

In addition, probable contact corrosion between dissimilar metals was investigated. These investigations were applied to the contact between the bolt material in the flange area and construction steels. The contact areas were assessed visually.

Table 4: Coating Systems

System number	SEM cross section	System composition (DFT)				Total DFT in µm
		Primer	2. Layer	3. Layer	4. Layer	
1		Zn-EP (80 µm)	EP (300 µm)	EP (300 µm)	PUR[1] (70 µm)	750
2		Zn-EP (80 µm)	EP (450 µm)	EP (450 µm)	-	980
3		Zn/Al (85/15)[2] (100 µm)	EP[3] (20 µm)	EP (450 µm)	EP (450 µm)	1,020
4		Zn/Al (85/15)[2] (100 µm)	EP[3] (20 µm)	EP[4] (450 µm)	EP[4] (450 µm)	1,020
5	No image available	EP[5] (1,000 µm)	-	-	-	1,000
6		Al/Mg (95/05)[2] (350 µm)	EP[6] (40 µm)	-	-	390

1) topcoat; 2) metallization; 3) primer + pore filler; 4) particle reinforced;
5) applied in one layer; 6) (pore filler); SEM - scanning electron microscopy

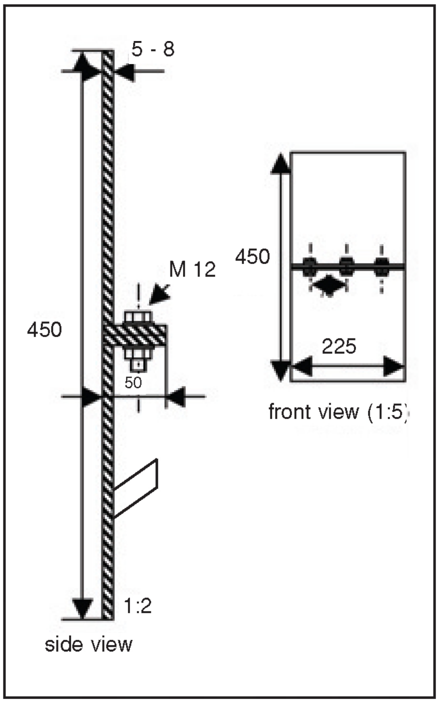


Fig. 7: Specimen design for splash zone (SZ); dimensions in mm
Courtesy of the authors

Test Samples

Outdoor Test Samples

Design rules for offshore wind energy tower follow the function of the tower. Low-corrosion design is a secondary issue. Therefore, the towers are complex structures with construction details such as bore holes, bolted connections, flanges, weld seams, bracings, steel sections, and coating overlap. Few approaches have been made in the past to consider these details. Bailey et al.[12] were probably the first to simulate construction details of offshore structures. Their specimen featured a plate with bore holes, I-beams, a pipe section, edges, weld seams, and bolts. Wilds[13] manufactured specimens containing a welded pipe section, angled parts, weld seams and I-beam, and he investigated the performance of organic repair coating systems. The author found a notable effect at the weld seams.

For the present study, researchers designed and manufactured three types of special specimens: for the UZ, for the IZ, and for the SZ (Figs. 6 to 8). The use of the specimens embodying on a small scale the typical structural features of a real offshore wind energy tower is considered a new approach in testing. All outdoor samples were made from high-strength, weldable construction steel, S-355.

The samples for the UZ were steel pipes. The pipes were filled with seawater and then sealed. These specimens contained weld seams at the uncoated and coated sections. They also featured a connection for cathodic protection (see Figs. 6 and 8). About 60% of the surface was coated. The specimens for the IZ zone were simple steel plates (Fig. 8). After an exposure for 13 months, researchers scribed the IZ samples to promote corrosion.

The specimens for the SZ consisted of two parts bolted together (Figs. 7 and 8). The lower part embodied the end of the foundation structure where the actual tower construction, embodied by the upper part of the specimen, rests. Both parts of the specimen featured a flange end, which was welded to the main body. The flange sections were metallized but not coated. Made from high-alloyed steel (AISI 304), the bolts represented the contact between dissimilar metals. The SZ specimens also contained an angled steel panel welded to the lower part. This construction detail may characterize design that promotes corrosion (Fig. 8).

Fig. 8: Coated specimens for outdoor testing. Upper: Splash zone (SZ) specimens. Center: Intermediate zone (IZ) (originally without scribe, no effect after 13 months; scribe added after 13 months to produce mechanical damage to the systems.) Bottom: Underwater (UZ) specimens
Courtesy of the authors

Laboratory Test Samples

Three types of laboratory samples were manufactured. The first type covered the specimens for the degradation tests according to ISO 20340.[2] The dimensions were slightly modified (Fig. 9). The coated specimens were provided with two artificial scribes to simulate localized mechanical damage. Position and dimensions of the scribes

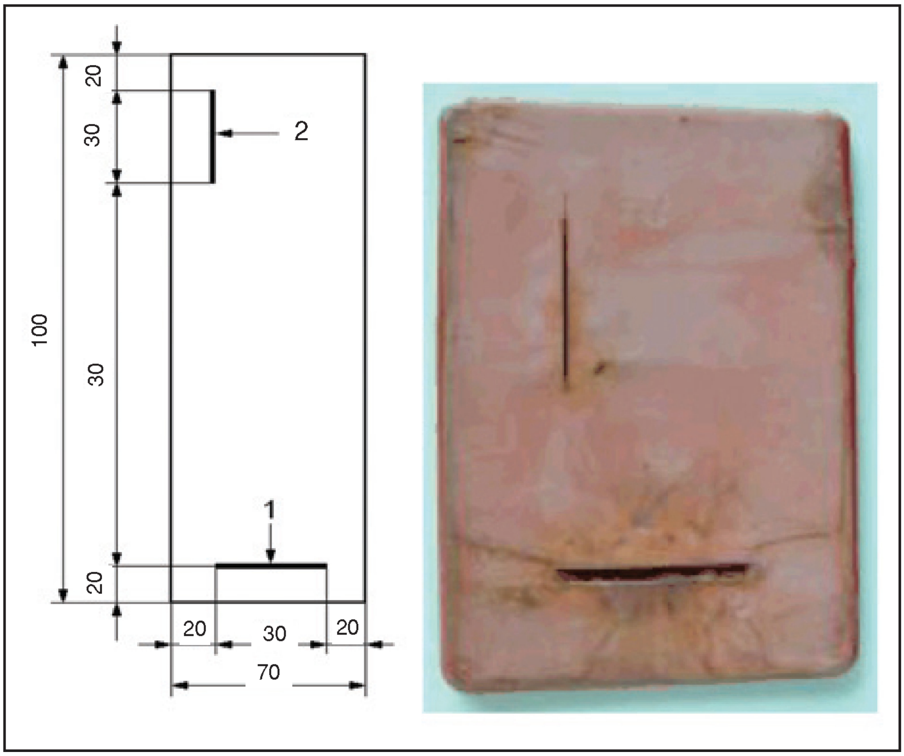


Fig. 9: Specimen design for the tests according to ISO 20340 (2); dimensions in mm
"1" = 2-mm-wide scribe; "2" = 0.05-mm-wide scribe
Courtesy of the authors

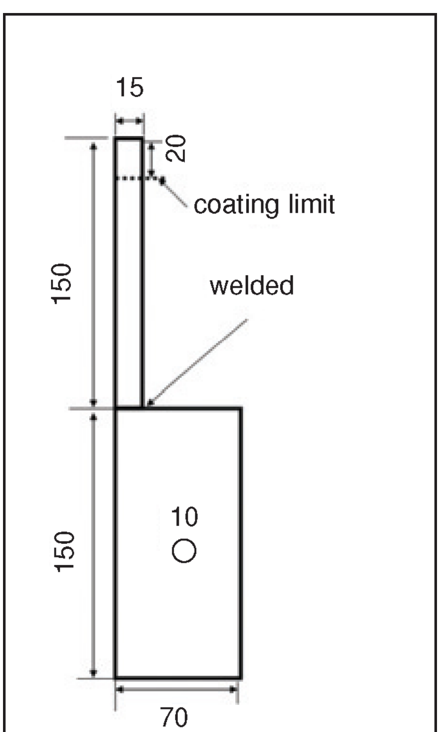


Fig. 10: Specimen design for the cathodic disbonding tests; dimensions in mm
Courtesy of the authors

can be read from Fig. 9. The second type covered the specimens for the cathodic disbonding tests (Fig. 10). The specimen consisted of a lower primary section and an upper, smaller secondary section, whereas the top part of the upper section remained uncoated. A hole with a controlled cross section (Ø 10 mm) was drilled through the coating down to the plain steel in the center of the specimen. The third specimen, used for EIS measurements, was a simple, coated plate 30 mm x 30 mm.

Coating Systems and Coating Materials

Corrosion protection scenarios can be subdivided into three categories: active methods, passive methods, and temporary methods. Active methods include the selection of corrosion-resistant materials, designs reducing the risk of corrosion, and cathodic protection. Passive methods include applying coatings or linings to protect the steel. The methods investigated in this project included the following:

- cathodic corrosion protection of unpainted steel;
- thick, single-layer organic coating,
- multi-layer organic coating system,
- duplex system: metal-sprayed coating with organic top coat, and
- metal-sprayed coating with organic sealer.

Details of these protection methods can be found in Table 4. Systems 1 and 2 are basic inexpensive versions, whereas the systems 3 and 4 represent more advanced versions. Systems 5 and 6 were applied to the samples for the UZ only.

The systems differed not only in terms of composition and thickness, but also in terms of primer coat and type of intermediate coat. The organic coating materials with particle reinforcement were non-commercial products. Duplex systems are routinely used for onshore wind energy towers, and they have been applied to offshore wind energy towers at places[6]. Duplex systems are high-level systems because the protection of steel against corrosion can be ensured even if the organic coating fails. Multi-layer organic coating systems are standard solutions, but their performance depends on the details of the systems. Therefore, multi-layer systems with different intermediate layers have been tested. Single-layer organic coating systems are not common in the offshore industry, but they could offer advantages in terms of application. Their performance under offshore conditions has not yet been investigated systematically. The system "Al/Mg-metallization + pore filler" is an uncommon variant for offshore constructions, but it would allow for a comparison between different metallization systems, Zn/Al and Al/Mg.[14]

All samples were blast cleaned according to ISO 8504-2.[15] Abrasive material was steel grit with a particle size between 0.2 and 2 mm. Fine cleaning was performed. The surface profile was measured with a stylus instrument according to ISO 8503-4.[16] The average maximum roughness had a value of R_{y5}=69 µm, with a standard deviation of 6 µm. The surface preparation grade was Sa 2½ (for the organic systems) and Sa 2½ to Sa 3 (for the metallized systems). The weld seams were ground and cleaned to a P3-quality according to ISO 8501-3.[17] All coatings were applied in accordance with the manufacturers' specifications. The organic systems were applied with airless spray systems. The metallized coatings were applied with a special metallizing technique[18] with the sample preparation and test program this described.

The second part of this article, to be published in an upcoming issue, will discuss the results of this testing.

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The authors can be contacted through Dr. Andreas Momber, momber@muehlhan.com