International Journal of Adhesion & Adhesives 65 (2016) 96–101

Contents lists available at ScienceDirect

International Journal of Adhesion & Adhesives

journal homepage: www.elsevier.com/locate/ijadhadh

The adhesion of corrosion protection coating systems for offshore wind power constructions after three years under offshore exposure

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ARTICLE INFO

Article history:
Accepted 28 November 2015
Available online 2 December 2015

Keywords:
Durability
Macro-tensile
Steels

ABSTRACT

Corrosion protection coating systems for offshore wind power constructions were subjected to offshore conditions on a test site in the North Sea. The systems included organic coatings and duplex (spray metal and organic system) coatings. Special exposure specimens were designed and manufactured and exposed to an offshore environment for three years in order to evaluate their protection performance. The adhesion in terms of pull-off strength and fracture mode was measured on coatings in the underwater zone and in the intermediate zone. All samples met the requirements for offshore ageing in terms of adhesion. An adhesion-based "corrosion protection effect" (C_E) is introduced and calculated for the coating systems.

1. Introduction

The installation of offshore wind power constructions is one of the most promising approaches for the production of renewable energies. These structures are ambitious engineering constructions. An offshore wind power structure basically consists of foundation, transition piece, tower construction, nacelle, and rotor blades. This article deals with corrosion protection systems for the transition piece and part of the foundation. Offshore wind power constructions are exposed to harsh and complex stresses, namely corrosive stresses, physical loads, and biological stresses. This paper deals with corrosive stresses, which is a major operational issue for offshore wind power constructions [1]. Corrosive stresses depend largely on the location of a structure. Offshore wind power constructions, as sea-based constructions, have 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 increases corrosion.
- Splash zone (SZ), the area wetted by wave and spray action, which can cause exceptionally high corrosion stresses, especially with sea water.

The environmental zones are illustrated in Fig. 1. Corrosion rate of construction steel in these environments can be as high as 2.5 mm per year [4]. This paper is concerned with the underwater zone and the intermediate zone. Two corrosivity categories must be considered for offshore wind power structures [3]:

- C5-M: very high, marine; coastal and offshore areas with high salinity;
- Im2: permanently immersed in sea water.

An important parameter to characterize coating protection capacity is adhesion strength between coating system and substrate [2,5]. Inadequate adhesion may promote failure of the coating and expose the substrate metal to the environment, causing corrosion [6]. Although adhesion strength numbers are reported for a number of laboratory offshore tests on coating systems [7,8], no systematic investigation has been performed for the adhesion of coatings for offshore wind power constructions after long-term performance under real offshore conditions. The objective of this paper is the investigation and assessment of the adhesion performance of two types of generic coating systems (duplex systems, organic systems) exposed to a real offshore environment in two environmental zones for a period of three years.

2. Test procedure and test samples

2.1. Test site conditions and test sample design

The test site was the seawater test site at the island of Helgoland, 70 km off the German coast. Site-specific environmental

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http://dx.doi.org/10.1016/j.ijadhadh.2015.11.011
0143-7496/

Fig. 1. Corrosion zones on offshore wind power structures, and sample exposure at the test site at Helgoland.

Table 1
Site-specific environmental conditions at Helgoland [9].

Parameter	Range
Salinity	29–33 PSU
Turbidity	Low–moderate
Light (PAR)	100– 2000 mol/m^2 s
Wave exposure	Exposed
Flow velocity	0.3–1.5 m/s
Specific wave height	0.5–4 m
Temperature	2–20 °C

conditions are provided in Table 1. The test site featured a gallery for underwater zone (UZ) environment and a gallery for intermediate zone (IZ) environment. Fig. 1 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. All samples were made from high-strength, weldable construction steel S-355. Steel thickness varied between 5 and 8 mm. The samples for the UZ, shown in Table 2, were steel pipes, reproducing foundation elements, such as monopiles or jacket bracings. About 60% of the external surface was coated. The specimens for the IZ, also shown in Table 2, were steel plates with the dimension 450 × 225 × 5 mm^3. Constructive details of the specimens are provided in [10].

2.2. Coating systems and preparation

Details of the coating systems are indicated in Table 3 and Fig. 2. The systems differed not only in terms of composition and thickness, but also in terms of primer coat and type of intermediate coat. Duplex systems, consisting of Zn/Al spray-metal and organic layers, are routinely used for onshore wind power structures, and they were applied to offshore wind power constructions in the past [11,12]. Duplex systems are high-level systems because the protection of steel against corrosion can be ensured even if the organic coating fails [10]. Multi-layer organic coating systems are standard solutions, but their performance depends on the details of the systems.

All substrate steel samples were blast-cleaned before coating application; abrasive material was steel grit with a particle size between 0.2 and 2.0 mm. Fine cleaning was performed in order to remove abrasive debris. The surface profile was measured with a mechanical stylus instrument according to [13]. The average maximum roughness was $Rz = 69$ µm, with a standard deviation of 6 µm. The surface preparation grade was Sa 2½ for the organic systems and Sa 3 for the duplex systems. These preparation grades are defined as follows [14]: for Sa 2½, "the surface shall be free from visible oil, grease and dirt, and from most of the mill scale, rust, paint coatings and foreign matter." For Sa 3, the same conditions apply, but the surface "shall have a uniform metallic color." 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 an arc-wire process according to [15].

2.3. Adhesion testing

The samples were tested according to the sandwich-method [16]. All samples were thoroughly cleaned after their release from the test site (see Table 2); see [10] for more details. Testing plates for adhesion testing were cut off the samples with a laboratory saw. The surfaces were carefully cleaned and degreased with methyl ethyl ketone (2-butanone) and were then slightly ground with P500 (30 µm) sanding paper. The adhesive was a 2-pack epoxy system (Araldite 2011) with an ultimate tensile strength of 33 MPa (ASTM D638). The mixing ratio was 100:80 wt%. The dolly diameter was 20 mm. After the dollies were glued, the adhesive cured for 12 h at 70 °C and 50% RH. After curing, the area covered by the dolly was separated from the surrounding coating through a separation cut around the dolly perimeter. Adhesion strength was evaluated as the ratio between fracture force and dolly cross section:

$$\sigma_A = \frac{F_F}{A}. \quad (1)$$

The fracture force was measured with a Zwick UTS (20 kN) tensile testing machine at a tensile stress rate of 0.8 MPa/s according to [16]. The tensile stress was applied in direction perpendicular to the plane of the coated substrate. The experimental set-up is shown in Fig. 3 The tests were performed at 23 °C and 50% RH. Six measurements were performed for each testing condition. The fracture types were estimated according to the assessment scheme in [16]. The fracture type designations are illustrated in Fig. 2 for an organic system and a duplex system. Basically, *adhesion* (interface) fractures (A/B, B/C, C/Y, B/Y) and *cohesion* (intra-material) fractures (B, C) can be distinguished. The percentage of each fracture type was estimated with an accuracy of 10% [16]. Six samples were evaluated for each testing condition.

3. Results and discussion

3.1. Results of pull-off testing

Table 4 lists results of pull-off tests for the underwater zone (UZ). The average pull-off strength values vary between 4.2 MPa and 9.4 MPa. These numbers are well above the minimum limit (2 MPa) stated in [2] for coatings after offshore testing. Although system 2 exhibits A/B fractures, its strength numbers are still above the limit of 5 MPa for this type of fracture [2]. There is no trend for particular coating system designations. Neither duplex nor plainly organic coatings have extraordinarily high pull-off