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Performance and integrity of protective coating systems for offshore wind power structures after three years under offshore site conditions

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ABSTRACT

Six corrosion protection systems for offshore wind power constructions have been subjected to offshore conditions on a test site in the North Sea in three different exposure zones, namely splash zone, intermediate zone, and underwater zone. The systems included single- and multiple-layered organic coatings, metal-spray coatings, and duplex coatings. Special testing specimens were designed and manufactured and exposed to an offshore environment for three years in order to characterize particular constructive details for different corrosivity zones. The following target parameters were investigated: intensity of fouling, anti-corrosive effect, coating adhesion, coating integrity, flange corrosion, coating performance over welds, and condition of screw connections. Fouling was an issue in the underwater zone and in the intermediate zone, but it did not affect the coating corrosion protection capacity. It was found that duplex systems, consisting of Zn/Al spray metallization, intermediate particle-reinforced epoxy coating, and polyurethane top layer, provided the highest anti-corrosive effect. Mechanical damage to the coatings initiated coating delamination and substrate corrosion. Effective coating systems should be either very resistant to impact or able to compensate for corrosion of the steel. Flange connections were found to be critical structural parts in the splash zone in terms of corrosion. Notable crevice corrosion was observed at places. Except for one coating system, welds have been protected well. Welds, however, affected the corrosion of the steel inside the uncoated internal sections in the underwater samples. Coating integrity on difficult-to-coat structural parts was satisfactory for all systems.

1. Introduction

The installation of offshore wind power constructions in both the North Sea and the Baltic Sea is one of the most promising approaches for the production of renewable energy. These structures are ambitious engineering installations. They can be as high as 80 m for offshore installations, the diameter can be as large as 7 m, and the wall thickness can be in the range of several centimetres. An offshore wind power structure basically consists of foundation, transition piece, tower construction, nacelle, and rotor blades. The tower is usually mounted to the transition piece by a bolted flange. This article deals with corrosion protection systems for the tower and part of the foundation. Offshore wind power constructions are exposed to harsh and complex stresses, including the following:

- corrosive stresses;
- mechanical stresses;
- biological stresses.

This paper deals mainly with corrosive stresses, which is a major operational issue for offshore wind power constructions [1,2]. Corrosive stresses include the following features: atmospheric marine exposure, seawater exposure, exposure to soil, wet–dry cycles, temperature variations, complex design (joints, bolts, welds), and materials pairings. Mechanical stresses include mechanical impact, and wave and current exposure. Biological stresses include basically fouling.

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 power constructions 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

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developed by the industry and regulatory bodies [3,4]. There are, however, critical differences between platforms and towers, the most significant being that offshore wind power constructions are unmanned structures with highly restricted access [5]. On oil and gas platforms, corrosion protection systems are generally under permanent inspection, which is not the case on offshore wind power structures. Moreover, wind tower constructions are subjected to corrosion fatigue. Another critical issue in corrosion protection of offshore wind power constructions is structural design. It is known that insufficiently designed constructive parts, namely weld seams, edges and corners, and difficult-to-access sections, promote coating deterioration and corrosion [2,6].

Corrosion protection performance and integrity of different surface protection systems for wind power installations on specially designed outdoor samples under offshore site conditions have not been systematically performed yet, and it is the objective of this paper to report about results of such a systematic study.

2. Corrosion protection systems for offshore wind power structures

Corrosive stresses depend largely on the location of a structure and the specific environmental conditions. For marine atmosphere conditions, affecting factors include the following [7]: relative humidity, duration of wetness, chlorides, temperature, and sunlight. For marine immersion conditions, the following factors are important [8,9]: seawater temperature, concentration of dissolved oxygen, water flow velocity, and nutrition pollution. Offshore wind power constructions, as sea-based constructions, have significant exposure in several zones, including the following [4,10]:

- 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 sea water.

The corrosion zones can be classified as per Fig. 1. Corrosion rate of steel in these environments can be greater than 2.5 mm per year [11]. It is already known that corrosion rates of steel are highest in the splash zone of offshore constructions (Table 1). The splash zone, which features the flange connection between transition piece 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 power structures [10]:

- C5-M (atmospheric): applies to coastal and offshore installations exposed to atmospheric conditions with high salinity, where high steel corrosion rates can be expected.
- Im2 (immersed): applies to installations permanently immersed in sea water.

Specifications for a corrosion protection system for offshore wind power constructions should address the following demands:

- high corrosive stress due to elevated salt concentration in both water and air;
- high corrosive stress due to fluctuating dry–wet cycles due to wave and water spray actions;
- mechanical loads due to ice drift or floating objects;
- biological stresses, namely under water;
- notable variations in temperature of both water and air;
- 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 [10]. If the categories are combined with a given durability range, general coating system schemes can be preselected [12]. The general scheme covers the following coating parameters: binder, primer type, number of coats, and nominal dry

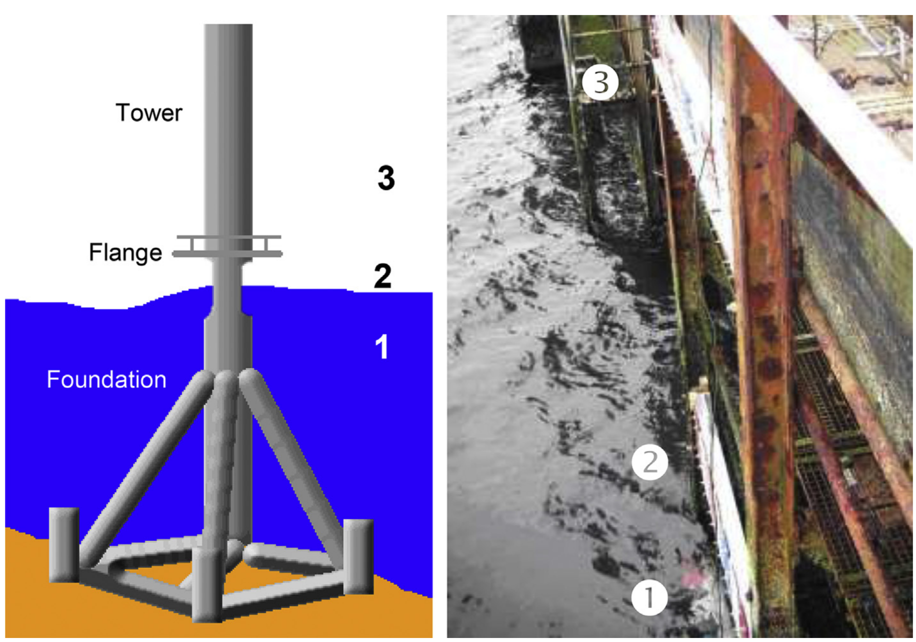

Fig. 1. Corrosion zones on offshore wind power structures investigated in this study (left) and outdoor test stand at Helgoland with specimens and corrosion zones (right) (Photographs: Offshore Wind Net; IFAM, Bremen). 1 – Underwater zone (UZ); 2 – Intermediate zone (IZ); 3 – Splash zone (SZ).