coatings

MDPI

Article

Assessment of Anti-Corrosion Performances of Coating Systems for Corrosion Prevention of Offshore Wind Power Steel Structures

Sung-Hyun Eom [1,*], Seong-Soo Kim [1] and Jeong-Bae Lee [2]

1 Department of Civil Engineering, Daejin University, 1007 Hoguk-ro, Pocheon-si 11159, Gyeonggi-do, Korea; sskim@daejin.ac.kr

2 GFC R&D., Ltd., 1007 Hoguk-ro, Pocheon-si 11159, Gyeonggi-do, Korea; dlwjdqo@nate.com

* Correspondence: aa216018@daejin.ac.kr; Tel.: +82-10-2032-6929

Received: 10 September 2020; Accepted: 9 October 2020; Published: 12 October 2020

Abstract: The anti-corrosion performance of coating systems (cathode protection, organic coating, and duplex coating) applied to prevent the corrosion of offshore wind power plants was assessed. As an assessment method, the adhesion strength of each coating system was evaluated after exposing the coatings to the marine environment and an indoor salt spray test. It was confirmed that the adhesion strength varied depending on the exposure period, and the deterioration of adhesion strength was related to the fracture type of each coating layer. In addition, the fracture type of each coating system was analyzed and the adhesion strength was corrected according to the fracture type. The corrosion rates after exposure to the marine environment and indoor salt spray were compared and examined using the corrected values.

Keywords: offshore wind power steel structures; corrosion; coating; adhesion strength; marine environment

1. Introduction

Offshore wind power plants are several tens of meters in height, more than 5 m in diameter, and several centimeters in outer wall thickness, and about 89% of them are made of steel materials. In such plants, the tower and jacket structures form the support structures. The tower ranges from the outer platform to the bottom of the nacelle, and the jacket ranges from the outer platform to the bottom of the steel pipe structure on the sea floor. Since the structures are located offshore, they are directly exposed to salt and are thus vulnerable to corrosion. Furthermore, they are neither easily accessible, nor is their maintenance straightforward [1].

In order to prevent corrosion of offshore wind power generation structures, quality standards and specifications of painting systems are defined based on the ISO 12944 series and corrosion prevention systems are applied to offshore structures such as petroleum and gas production platforms. However, the ISO specification is not the only factor when selecting the coating system [2,3].

The corrosion protection coating system used for each zone of an offshore wind power structure is based on the environmental conditions of each zone; for example, the influence of the high weather ability, temperature, salt spray and wetting should be considered for atmosphere-exposed zone. In the case of the tidal zone, it is necessary to consider the combined effect of external force, temperature and seawater immersion due to tidal change. In the case of the underwater zone, a painting system reflecting the negative voltage environment due to the use of the electric method is applied [4].

Unlike other offshore plants such as oil and gas extraction platforms, offshore wind power plants are unmanned structures with limited access. Therefore, continuous corrosion inspection and monitoring is significantly limited [5]. Furthermore, the corrosion of offshore plants is assessed by the corrosion (erosion) of the iron used, and no standard method is available to assess the coating systems used to prevent the corrosion of plants [6].

A.W. Momber et al. evaluated the corrosion resistance of offshore wind power structures, and found that the effects of uncoated sections, pins, low film thickness, mechanical impacts, and wrong material selection resulted in heavy rust, deep pitting, and metal loss. It is expected that most of the structures will not meet the coating life expectancy of 15 years [7].

The coating industry has continuously improved the coating technology used to protect offshore structures, which are hundreds of miles away from the land. However, as described above, it is difficult to inspect regularly the protective coating of offshore wind power generation structures, and corrosion protection performance of coatings cannot be assessed unless systematic investigation of the coating system used on the offshore wind power generation platform is performed.

The most important parameter that affects the anti-corrosion performance of a coating system is the adhesion strength between the coating system and the underlying surface. The adhesion strength is an important fundamental feature of a coating system and is used to determine the strength with which the system is attached to a surface. A coating system with insufficient adhesion accelerates the separation of the coated film and exposes the surface to corrosive environments, resulting in corrosion of the structure [8].

While many studies have been conducted on the adhesion strength of coating systems, studies of the variation in adhesion strength according to exposure period under marine environmental conditions are not sufficient [9].

This study analyzed the adhesion performance of coating system (surface protective paint, metal spraying, duplex coating) applied for corrosion protection in offshore wind power structures. Through the test, which comprised a long-term exposure of coating samples to marine conditions and to brine conditions indoors, the adhesion performance maintenance lifetime of coating systems for offshore wind power structures were analyzed.

2. Test Sample Fabrication

SS400 standard structural steel was used in this study. All the steel materials were surface-treated to Sa2 1/2 standard (removal of visible foreign matter such as oil, dust, scale, and rust, which are visible to the naked eye) according to ISO 8501-1 [10]. The coating systems examined in this study were Zn–Al metal spraying (MS), Zn–Al metal spraying + epoxy coat (MC), epoxy coat (TP), and epoxy coat + polyurethane coat (EP), all of which are applied to offshore structures. Table 1 shows the coating specifications of each coating system.

Table 1. Coating systems.

Abbreviation	System Composition (Dry Film Thickness, DFT, μm)				Total DFT (μm)
	1.Layer	2.Layer	3.Layer	4.Layer	
MS	Zn 85% + Al 15% (100)				100
MC	Zn 85% + Al 15% (100)	Epoxy (75)	Epoxy (200)	Epoxy (50)	425
TP	Epoxy (75)	Epoxy (375)	Epoxy (50)	-	500
EP	epoxy (200)	epoxy (200)	epoxy (200)	poly urethane (70)	670

Zn 85% + Al 15%: weight-ratio. After metal spraying—sealing (not included in coating thickness).

The test samples were fabricated as steel plates with dimensions of 150 mm × 75 mm × 6 mm, as recommended by ISO 1514 [11]. Although ISO 1514 suggests a steel plate thickness of 3 mm, the plate thickness employed in this study was 6 mm for the adhesion strength test method for corrosion damage assessment of coating systems.

3. Assessment Method

3.1. Anti-Corrosion Performance Assessment

In this study, the variation in the adhesion strength of anti-corrosion coating systems applied to offshore wind power plants was measured and assessed after 365 days of exposure to a marine environment and 15 days of indoor salt spray test (CASS). The adhesion strength was assessed according to ASTM D 4541 [12]. When foreign matter or corrosion products (corrosion product of zinc: white rust) were present on the measurement area, the surface was cleaned using a sandpaper with more than 400 grit and high-pressure water. After bonding a Ø20-mm dolly to the measurement area, the adhesion strength was measured using a Posi Test AT-A adhesion tester. Three samples were used for each coating system and measurements were conducted in three zones. Furthermore, the visual observations of the damage to the coating systems caused by exposure to marine environment and salt spray were compared with the adhesion strength variation caused by the damage to the coating systems [12].

3.2. Sea Exposure and Indoor Tests

The corrosion damage to the coating systems under marine environmental conditions was assessed by exposing the coating systems to sea at a site located in Daebu Island, Korea. In the test site, the coatings were exposed to the underwater zone, tidal zone, and atmosphere zone. Table 2 shows the environmental conditions of the test site.

Table 2. Environmental conditions of the test site.

Environmental Condition	Exposed Zone	Range
average temperature	atmosphere zone /tidal zone	12.5 °C
average relatively humidity	atmosphere zone /tidal zone	70.4%
average wind velocity	atmosphere zone	7.1 m/s
solar irradiance	atmosphere zone	4735.78 MJ/m^2
ultraviolet ray exposure	atmosphere zone	157.71 MJ/m^2
airborne chlorides	atmosphere zone	38.5 mg/dm^2/day
pH	tidal zone /underwater zone	8.3
salinity	underwater zone	31~33 PSU
depth the coatings were exposed in the underwater zone	underwater zone	2 m
height above sea level in the atmosphere zone.	atmosphere zone	10 m

An indoor corrosion exposure test method was used for corrosion assessment by simulating the marine environmental conditions indoors according to the ASTM B 368 salt spray test method. Table 3 shows the conditions of the indoor corrosion exposure test method [13].

Table 3. Conditions during salt spray test (ASTM B 368).

Item	Unit	Test Condition
NaCl concentration	g/L	40
$CuCl_2$ solution concentration	g/L	0.205
pH	-	3.0
Compressed air pressure	kgf/cm^2	1.0
Spraying solution	ml/80 m^2/h	2.0
Air saturator temperature	°C	63 ± 2
Salt water tank temperature	°C	50 ± 2
Test bath temperature	°C	50 ± 2

4. Results and Discussion

4.1. Adhesion Strength after Exposure to the Marine Environment

Figure 1a–c show the adhesion strength as a function of sea exposure period. The total sea exposure period was 365 days. As shown in Figure 1a, in the case of exposure to the offshore tidal zone, the adhesion strength of MS dramatically decreased after 90 days of exposure; after 365 days, it was near to 5 MPa, which is the minimum adhesion strength for offshore structure coating systems recommended by ISO 12944-9 [2]. After 365 days of exposure to the tidal zone, the adhesion strengths of MC and TP decreased by approximately 29% compared to their respective initial values; however, they still exhibited strengths of 11.1 and 9.3 MPa, respectively. For EP, the change in adhesion strength was insignificant regardless of the exposure period.

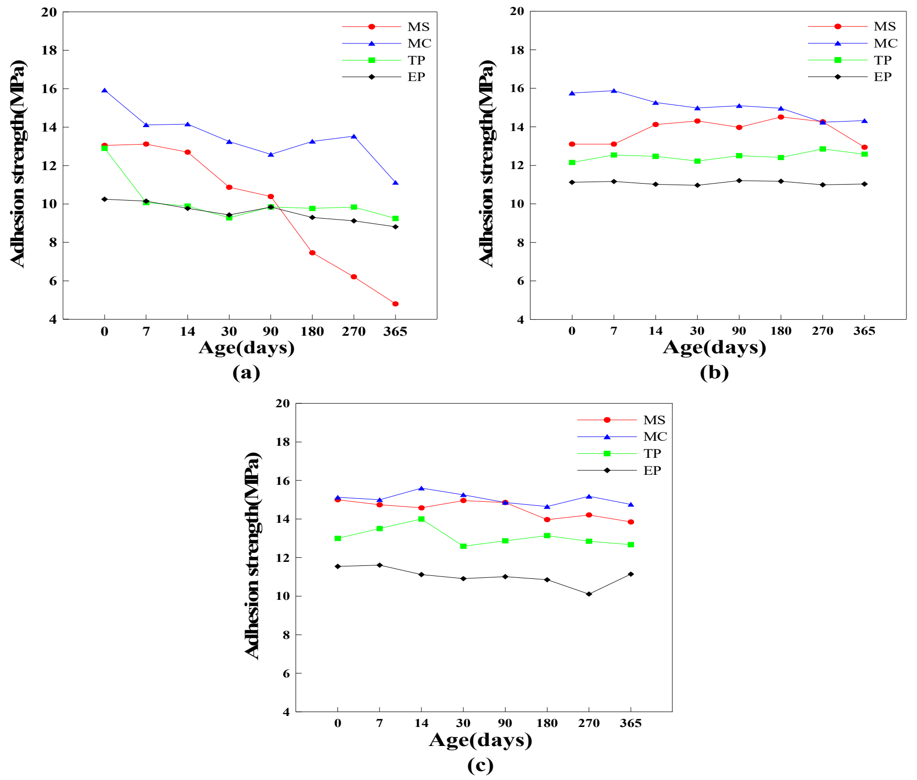


Figure 1. Adhesion strength of coating systems exposed to (**a**) tidal zone, (**b**) atmosphere zone, (**c**) underwater zone.

In the offshore exposure test, the atmosphere zone simulated the marine environment of the tower structures of offshore wind power plants. In this environment, structures are vulnerable to corrosion because they are affected by airborne chlorides. The airborne chlorides of the atmosphere zone used in this study were 0.8~16.0 mg/dm^2/day, which represented the highest amount of airborne chlorides in South Korea [14]. As shown in Figure 1b, after 365 days of exposure, for MC, the adhesion strength was lower than that at the initial stage, but converged after 270 days. In other coating systems (MS, TP, EP), it was confirmed that there was no change in adhesion strength.

Figure 1c shows the change in adhesion strength after 365 days of exposure to the underwater zone. For all the coating systems, the change was insignificant regardless of the exposure period.

4.2. Adhesion Strength after Salt Spray Test

To examine the variation in adhesion strength of the four coating systems, salt was sprayed onto each coating system for 15 days using the ASTM B 368 salt spray test method, and the adhesion strength was examined as a function of test period.

Figure 2 shows the adhesion strengths measured on alternate days for 15 days of salt spray. The adhesion strengths of all the coating systems tended to decrease with increase in exposure time. After 15 days of salt spray, the adhesion strengths of MS, MC, TP, and EP decreased by 46%, 35%, 60%, and 50%, respectively. In particular, TP and EP exhibited adhesion strengths near to 5 MPa, which is the minimum adhesion strength for offshore structure coating systems stipulated by ISO 12944-9. In the salt spray test, the adhesion strength reduction rate of MS was 46% (after 15 days), whereas the highest adhesion strength reduction rate of 75% was obtained upon exposure to the offshore tidal zone. For TP and EP, the adhesion strength reduction rates were higher for salt spray exposure than for exposure to the offshore tidal zone (28% and 14%, respectively).

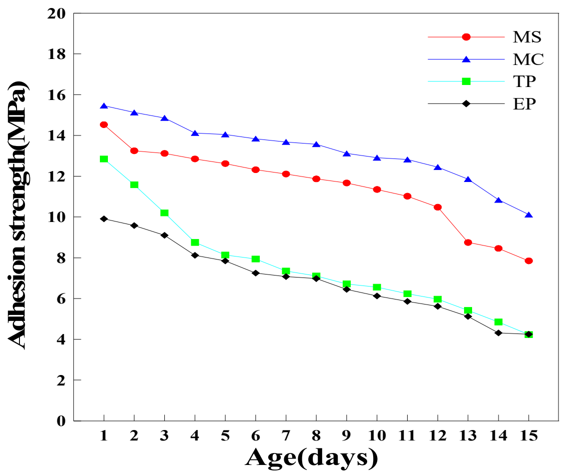


Figure 2. Adhesion strength of coating systems after salt spray test.

4.3. Fracture Type after the Adhesion Strength Test

When a coating system is exfoliated at certain adhesion strength, ISO 4624 specifies that the fracture area of each coating layer should be indicated by measuring the area of the exfoliated coating [15]. While only a single coat is sufficient for some coating systems, offshore steel structures require three or more coats of heavy-duty coatings. Accordingly, the adhesion strength notation of ISO 4624 represents the fracture area of the exfoliated coating layer together with the adhesion strength, considering the adhesion strength between the coating system and the surface as well as that between each coating layer. Figure 3 shows the coating layers and fracture shape of each coating system. After the adhesion strength of each sample subjected to sea exposure and salt spray was measured, the fracture type of the coating layer was analyzed.

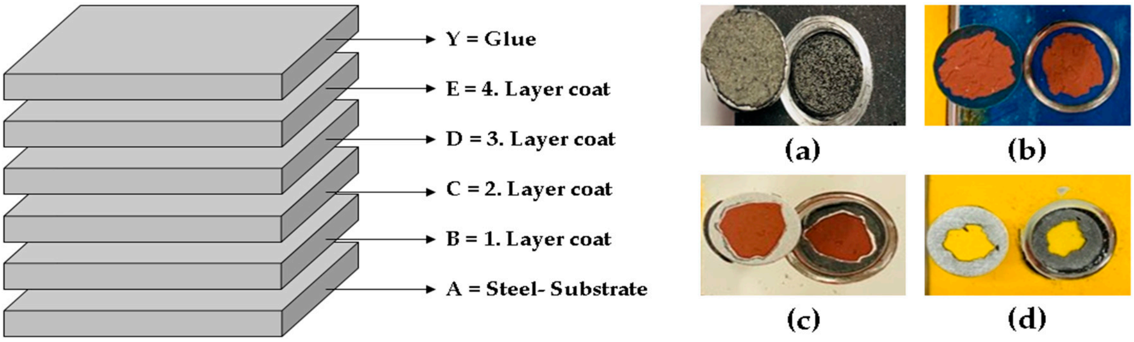


Figure 3. Coating layer fracture shape of each coating system: (**a**) Zn–Al metal spraying (MS), (**b**) Zn–Al metal spraying + epoxy coat (MC), (**c**) epoxy coat (TP), (**d**) epoxy coat + polyurethane coat (EP).

Tables 4–7 show the adhesion strengths and fracture types of the coating systems according to the period of exposure.

Table 4. Adhesion test results of coating systems exposed to tidal zone.

Type	Age (Days)	Fracture Mode
MS	0	Y = 100%
	90	B = 20%, Y = 80%
	180	A/B = 10, B = 90%
	365	A/B = 70, B = 30%
MC	0	E/Y = 100%
	90	D/E = 10%, E/Y = 90%
	180	E/Y = 100%
	365	D/E = 10%, E/Y = 90%
TP	0	D/Y = 100%
	90	C/D = 10%, D = 10%, D/Y = 80%
	180	D = 10%, D/Y = 90%
	365	D = 10%, D/Y = 90%
EP	0	D = 10%, D/E = 10%, E/Y = 80%
	90	E = 30%, E/Y = 70%
	180	D/E = 20%, E/Y = 80%
	365	C/D = 20%, D/E = 10%, E/Y = 70%

Table 5. Adhesion test results of coating systems exposed to atmosphere zone.

Type	Age (Days)	Fracture Mode
MS	0	Y = 100%
	90	Y = 100%
	180	Y = 100%
	365	Y = 100%
MC	0	E/Y = 100%
	90	E/Y = 100%
	180	E/Y = 100%
	365	E/Y = 100%
TP	0	D/Y = 100%
	90	D/Y = 100%
	180	D/Y = 100%
	365	D/Y = 100%
EP	0	E/Y = 100%
	90	D/E = 20%, E/Y = 80%
	180	E/Y = 100%
	365	D/E = 10%, E/Y = 90%

Table 6. Adhesion test results of coating systems exposed to underwater zone.

Type	Age (Days)	Fracture Mode
MS	0	Y = 100%
	90	Y = 100%
	180	Y = 100%
	365	Y = 100%
MC	0	E/Y = 100%
	90	E/Y = 100%
	180	E/Y = 100%
	365	E/Y = 100%
TP	0	D/Y = 100%
	90	D/Y = 100%
	180	D/Y = 100%
	365	D/Y = 100%
EP	0	D/E = 10% E/Y = 90%
	90	D = 10%, D/E = 20%, E/Y = 70%
	180	D = 20%, D/E = 10%, E/Y = 70%
	365	C/D = 10%, D/E = 20%, E/Y = 70%

Table 7. Adhesion test results of coating systems exposed to salt spray test (ASTM B 368).

Type	Age (Days)	Fracture Mode
MS	0	Y = 100%
	5	Y = 100%
	10	B = 30%, Y = 70%
	15	A/B = 30%, B = 30%, Y = 40%
MC	0	E/Y = 100%
	5	E/Y = 100%
	10	D/E = 20%, E/Y = 80%
	15	C/D = 10%, D/E = 20%, E/Y = 70%
TP	0	C/D = 20%, D/Y = 80%
	5	B/C = 20%, C/D = 20%, D/Y = 60%
	10	B/C = 30%, C/D = 30%, D/Y = 40%
	15	A/B = 10%, B/C = 30%, C/D = 20%, D/Y = 40%
EP	0	C/D = 10%, D/E = 20%, E/Y = 70%
	5	B/C = 20%, C/D = 20%, D/E = 10%, E/Y = 50%
	10	A/B = 10%, B/C = 10%, C/D = 20%, D/E = 20%, E/Y = 40%
	15	A/B = 40%, B/C = 30%, C/D = 20%, D/E = 10%

Table 4 shows the adhesion strength and fracture type of each coating system exposed to the offshore tidal zone. For MS, Y = 100% fracture occurred when the adhesion strength was 13.1 MPa before exposure. After 365 days of exposure, the adhesion strength reduced by 75% to 3.1 MPa, with fracture type A/B = 70% and B = 30%. For MC, the adhesion strength was 15.9 MPa before exposure and 11.1 MPa after 365 days of exposure. At 11.1 MPa, fracture with D/E = 10% and E/Y = 90% occurred. For TP and EP, fractures with D = 10% and D/Y = 90% and that with C/D = 20%, D/E = 10%, and E/Y = 70%, respectively, occurred, and slight fractures between the coating layers appeared.

Table 5 shows the adhesion strength and fracture type of each coating system sample exposed to the offshore atmosphere zone. The adhesion strength reduction of the samples exposed to the atmosphere zone was insignificant, and it was confirmed that adhesion between the coating layers was excellent because the dolly adhesive part was exfoliated in all the samples.

Table 6 shows the adhesion strength and fracture type of each coating system sample exposed to the offshore underwater zone. For MS, MC, and TP, the adhesion strength reductions were insignificant after 365 days of exposure to the underwater zone. For EP, the change in adhesion strength was insignificant for the entire exposure period of 365 days; however, fracture with C/D = 10%, D/E = 20%, and E/Y = 70% occurred after 365 days, confirming that the adhesion between the coating layers deteriorated.

Table 7 shows the adhesion strength and fracture type of each coating system sample subjected to the indoor salt spray test (CASS). The fracture type was analyzed for 0, 5, 10, and 15 days. For MS, 30% fracture occurred in the Zn–Al metal spray coating layer after 10 days of salt spray, and 70% fracture appeared in the dolly adhesive layer. After 15 days of salt spray, fracture with A/B = 30%, B = 30%, and Y = 40% occurred, confirming that the adhesion between the sample surface and the Zn-Al metal spray coating layer had decreased. For MC, fracture with D/E = 20% and E/Y = 80% occurred after 10 days of salt spray, while fracture with C/D = 10%, D/E = 20%, and E/Y = 70% appeared after 15 days of salt spray. For TP, fracture with B/C = 20%, C/D = 20%, and D/Y = 60% occurred after five days of salt spray and that with A/B = 10%, B/C = 30%, C/D = 20%, and D/Y = 40% appeared after 15 days of salt spray, confirming that fracture occurred on the sample surface and in all the coating layers. For EP, fracture with A/B = 40%, B/C = 30%, C/D = 20%, and D/E = 10% appeared after 15 days of salt spray. In particular, 40% fracture occurred between the sample surface and the 1st coating layer, confirming that the adhesion of the 1st coating had significantly lowered.

Thus, in this study, by measuring the adhesion strength from the sample surface to each coating layer, it was confirmed that the fracture type varied as the adhesion strengths of the coating systems changed.

When fracture occurred in the glue between the top layer and the dolly of the coating system, the adhesion strength reduction was insignificant, and the coating system specimen was not damaged. In addition, when the adhesion strength decreased, fracture occurred from the coating layer beneath the top layer. When the fracture rates of the coating layers, except for the A/B layers, were 20% or less, the change in adhesion strength was insignificant. When fracture occurred at A/B, the adhesion strength decreased significantly compared to that before exposure. In particular, the coating system sample was somewhat damaged and swelling of the coating was also observed. In conclusion, defects between the surface and the coating system (A/B) not only decrease the adhesion strength, but also act as a factor that significantly deteriorates the anti-corrosion performance.

4.4. Correction of Adhesion Strength

As discussed in Section 4.3, the fracture type between coating layers varied depending on the degree of damage to the coating system when the adhesion strength was measured. In particular, when fracture occurred at A/B (surface/1st coating), the adhesion of the surface/1st coating interface lowered and the possibility of critical corrosion of the surface increased [16].

In addition, fracture between the coating layers degraded the performance of the coating system, which was used to prevent the corrosion of steel materials, because of the lack of functionality of the coating type constituting the coating layers.

A.W. Momber et al. determined the fracture type between each coating layer as a factor when measuring the adhesion strength, and assessed the corrected adhesion strength, i.e., the corrosion prevention effect, C_E, according to the adhesion strength by applying the fracture type factor to the measured adhesion strength [9].

$$C_E = \frac{\beta}{\alpha_1 \cdot \alpha_2} \tag{1}$$

where, β is the adhesion strength (MPa), and α_1, α_2 are correction factors.

Table 8 shows the correction factor according to the fracture type after adhesion strength measurement. α_1 and α_2 are the fracture type factors, and the corrosion prevention effect remarkably improves as the C_E increases. α_1 is the fracture type factor (area, %) for the fracture of the A/B coating section (see Figure 3), and α_2 is the fracture type factor (area, %) for the fracture of the coating layers above the B coating section.

Table 8. Fracture type correction factor (by Momber et al.) [9].

Fracture Type A/B in %/Other Fracture Types in %	0	10	20	30	40	50	60	70	80	90	100
Coefficient α_1	1.00	1.15	1.30	1.45	1.60	1.75	1.90	2.05	2.20	2.35	2.50
Coefficient α_2	1.00	1.01	1.02	1.03	1.04	1.05	1.06	1.07	1.08	1.09	1.10

In this study, the adhesion strengths were corrected using the fracture type factor proposed by Momber et al. Figure 4 shows the corrected adhesion strengths. When 100% fracture occurs in the dolly used for measuring the adhesion strength and the glue of the top coating layer, the coating system is considered to have no defect, and thus, the A/B fracture type (area) is 0% and α_1 and α_2 are 1.00. The corrected adhesion strengths of the four coating systems examined in this study, which were corrected according to the fracture type, were lower than the initial adhesion strengths when the fracture area between the coating layers was large. Furthermore, the corrected values were significantly lower than the initial values when fracture occurred between the sample surface and the 1st coating (A/B) and the fracture area was large. As described in this section, C_E represents the corrosion prevention effect of the coating system, the fracture of A/B directly provides the area where the sample surface is exposed to a corrosive environment, and fracture between the coating layers acts as a factor that degrades the corrosion prevention function of each coating layer and lowers the corrosion prevention performance of the entire coating system [8].

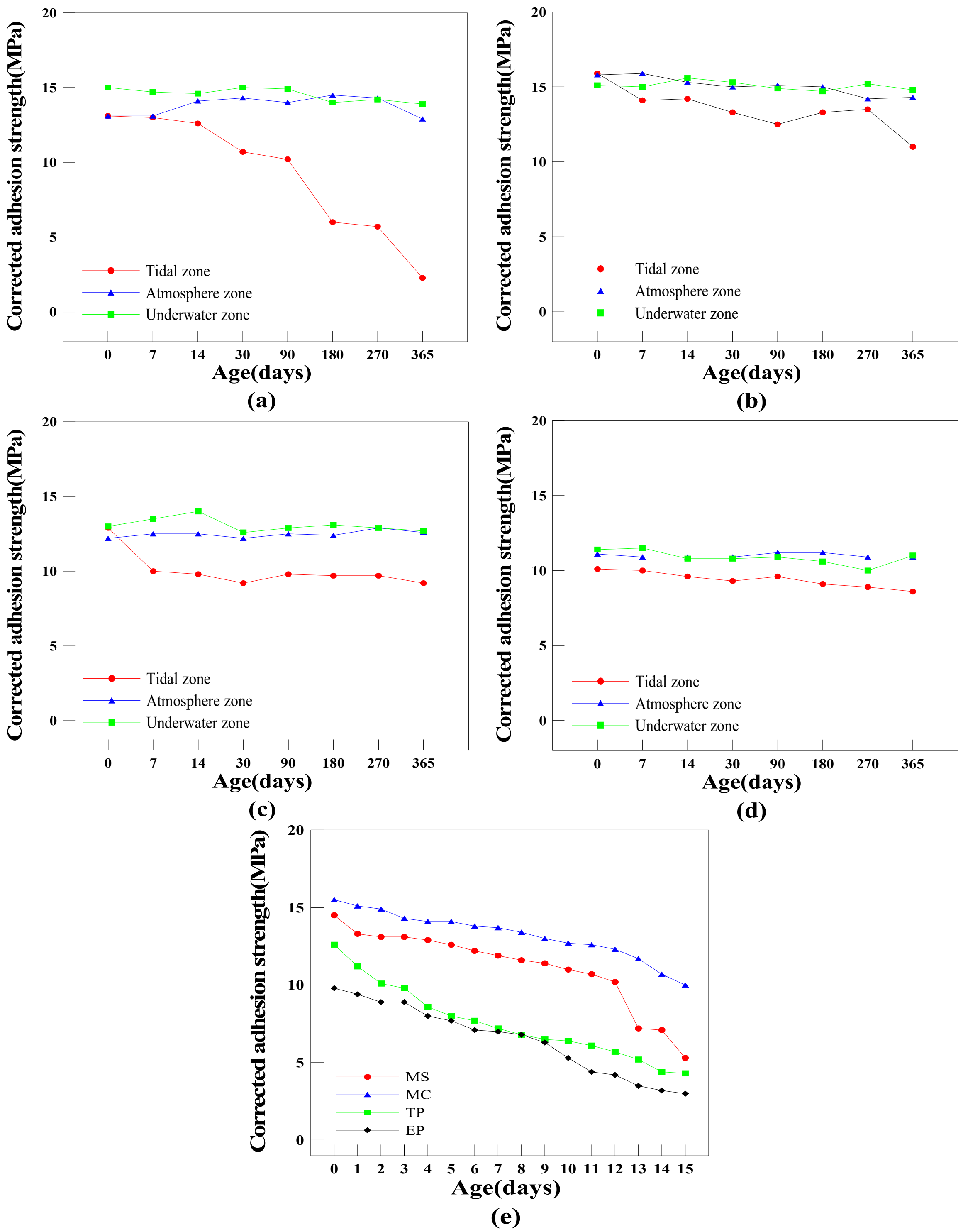


Figure 4. Corrected adhesion strength of (**a**) MS, (**b**) MC, (**c**) TP, (**d**) EP and corrected adhesion strength of coating systems after salt spray test (**e**).

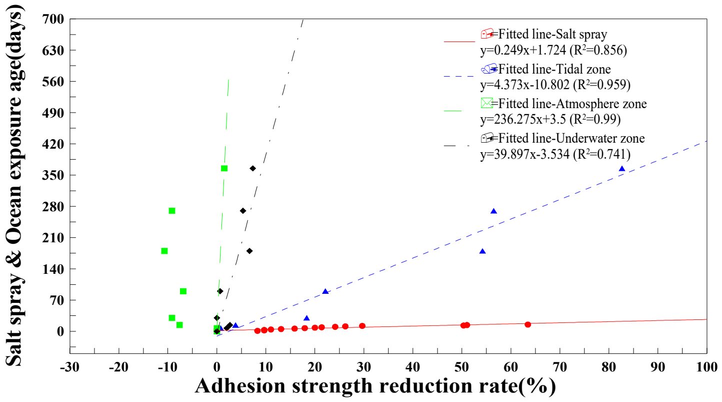
These results suggest that the fracture type must be analyzed when the corrosion prevention performance of a coating system in terms of the adhesion strength is considered because adhesion strength correction (corrosion prevention effect, C_E) varies depending on the fracture type between the coating layer, even if the initial adhesion strength of the coating system is high.

4.5. Corrosion Rate Comparison between the Indoor Corrosion Acceleration Test and Sea Exposure Test

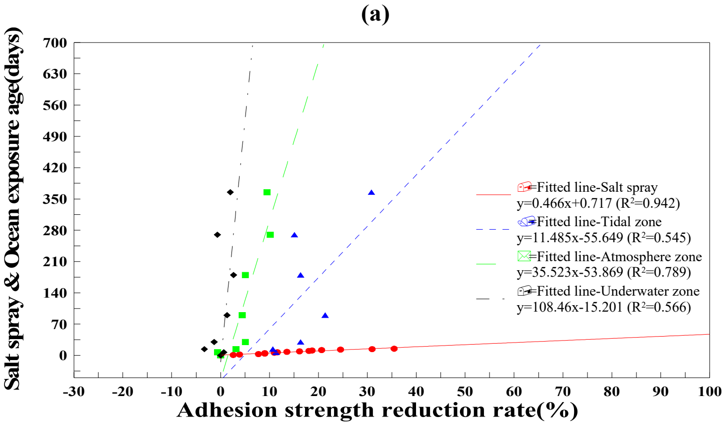
In this study, the corrosion rate (%) of each coating system measured by the corrosion acceleration test conducted in the laboratory was compared with that of the exposure test. In addition, the time of corrosion occurrence in each coating system derived from the indoor corrosion acceleration test and that obtained from exposure to marine environment were examined.

ISO 12944-9 specifies that the coating system used for offshore structures should meet 50% of the initial value after the aging test (NORSOK M-501). In this study, the occurrence of corrosion in each coating system was judged to be corrosion when the adhesion strengths were less than 50% compared with the initial adhesion.

Figure 5 shows the corrosion rate (compared to the initial value) of each coating system as a function of exposure period after the salt spray test and sea exposure test (corroded area). The period of the salt spray test was 15 days and that of the sea exposure test was 365 days.



(a)



(b)

Figure 5. *Cont.*

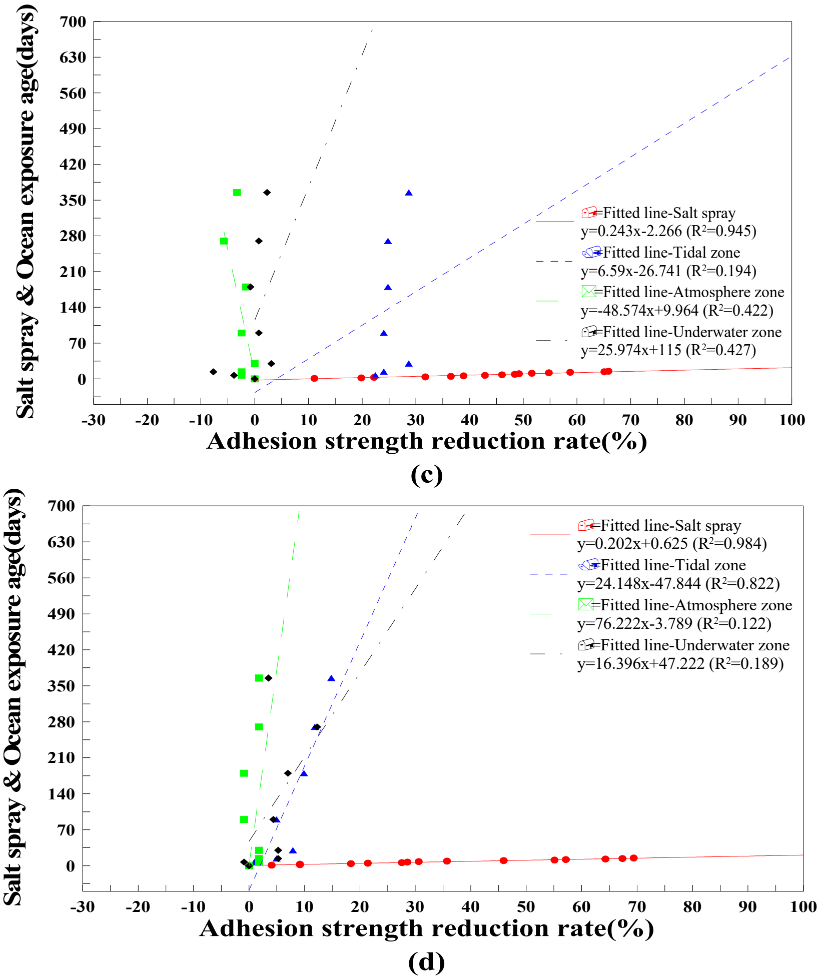


Figure 5. Comparison of corrosion rate of (**a**) MS, (**b**) MC, (**c**) TP, (**d**) EP.

For MS (Figure 5a), the 50% corrosion rate occurred after 15 days of the salt spray test as well as after approximately 180 days of exposure to the tidal zone.

For MC (Figure 5b), the corrosion rate did not reach 50% during the salt spray test period, and the corrosion rate during sea exposure was not high, indicating that long-term corrosion exposure test results are required.

For TP and EP (Figure 5c,d), the corrosion rates were 50% after 9–10 days of the salt spray test. For exposure to the tidal zone, TP achieved 50% corrosion rate in a significantly shorter time than EP did. It was found that EP achieved 50% corrosion rate after 1–2 years when exposed to the underwater zone.

For sea exposure, comparison of corrosion timing with that of the salt spray test was possible only for the tidal zone where the corrosion rate changed significantly. For the atmosphere and underwater zones, however, long-term sea exposure test results are required to compare the corrosion timing with that of the salt spray test, except for some cases where the corrosion rate of the coating system changed.

5. Conclusions

The results of this study can be summarized as follows.

(1) When fracture occurred from the coating layer beneath the top coating of the coating system, the adhesion strength deteriorated depending on the fracture type. When fracture occurred between the surface and the 1st coating, the adhesion strength significantly decreased compared to that before exposure.

(2) The corrected value of the measured adhesion strength according to the fracture type (corrosion prevention effect, C_E) was affected by the fracture area between the coating layers and the fracture type between the surface and the 1st coating. In particular, if fracture occurs between the surface and the 1st coating in all the coating systems, the corrected adhesion strength would become significantly lower than the initial value.

(3) For exposure to the tidal zone, the corrosion rate (%) of each coating system after exposure to marine environment could be compared with that after the indoor salt spray test using the corrosion rate data for one year of exposure to marine environment. For the atmosphere zone and underwater zone, long-term sea exposure test results are required.

(4) In terms of in accordance with adhesion strength (anti-corrosion performance) by types and structure positions of the coating system applied on offshore wind power structures, Zn–Al metal spraying + epoxy coat (MC), epoxy coat (TP), epoxy coat + polyurethane coat (EP) type coating systems would be suitable for offshore wind power steel structures.

Author Contributions: Conceptualization, S.-H.E.; methodology, S.-H.E. and J.-B.L.; validation, S.-S.K. and J.-B.L.; formal analysis, S.-S.K.; investigation, S.-H.E.; resources, J.-B.L.; data curation, S.-S.K.; writing—original draft preparation, S.-H.E.; writing—review and editing, S.-H.E. and J.-B.L.; visualization, S.-H.E.; project administration, S.-S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20153030023600).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lee, J.-H.; Jung, K.-H.; Park, J.-C.; Kim, S.-J. Determination of optimum protection potential for cathodic protection of offshore wind-turbine-tower steel substructure by using potentiostatic method. *J. Korean Soc. Mar. Eng.* **2017**, *41*, 230–237. [CrossRef]
2. ISO 12944-5. *Paints and Varnishes—Corrosion Protection of Steel Structures by Protective Paint Systems—Part 5: Protective Paint Systems*; International Organization for Standardization: Geneva, Switzerland, 2016.
3. ISO 12944-9. *Paints and Varnishes—Corrosion Protection of Steel Structures by Protective Paint Systems—Part 9: Protective Paint Systems and Laboratory Performance Test Methods for Offshore and Related Structures*; International Organization for Standardization: Geneva, Switzerland, 2018.
4. Axelsen, S.B.; Knudsen, O.Ø.; Johnsen, R. Protective Coatings Offshore: Introducing a Risk-Based Maintenance Management System—Part 1: Risk Analysis Methodology. *Corrosion* **2009**, *65*, 809–816. [CrossRef]
5. Versowsky, P.E. Rationalization and optimization of coatings maintenance programs for corrosion management on offshore platforms. *NIST Spec. Publ.* **2005**, *1035*, 170–177.
6. DNV GL-ST-0126. *Support Structures for Wind Turbines*; DNV-GL: Oslo, Norway, 2016.
7. Momber, A. Quantitative performance assessment of corrosion protection systems for offshore wind power transmission platforms. *Renew. Energy* **2016**, *94*, 314–327. [CrossRef]
8. Sørensen, P.A.; Kiil, S.; Dam-Johansen, K.; Weinell, C.E. Anticorrosive coatings: A review. *J. Coat. Technol. Res.* **2009**, *6*, 135–176. [CrossRef]
9. Momber, A.; Plagemann, P.; Stenzel, V. The adhesion of corrosion protection coating systems for offshore wind power constructions after three years under offshore exposure. *Int. J. Adhes. Adhes.* **2016**, *65*, 96–101. [CrossRef]
10. ISO 8501-1. *Preparation of Steel Substrates before Application of Paints and Related Products—Visual Assessment of Surface Cleanliness—Part 1: Rust Grades and Preparation Grades of Uncoated Steel Substrates and of Steel Substrates after Overall Removal of Previous Coatings*; International Organization for Standardization: Geneva, Switzerland, 2007.
11. ISO 1514. *Paints and Varnishes—Standard Panels for Testing*; International Organization for Standardization: Geneva, Switzerland, 2016.
12. ASTM D 4541. *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers*; ASTM International: West Conshohocken, PA, USA, 2017.

13. ASTM B 368. *Standard Test Method for Copper-Accelerated Acetic Acid-Salt Spray (Fog) Testing (CASS Test)*; ASTM International: West Conshohocken, PA, USA, 2014.
14. Lee, J.-S. *Long Term Measurement of Airborne Chlorides and Durability of Concrete Mixed with Sea Sand*; KICT: Goyang, Korea, 2006. [CrossRef]
15. ISO 4624. *Paints and Varnishes—Pull-Off Test for Adhesion*; International Organization for Standardization: Geneva, Switzerland, 2016.
16. Spengler, E.; Margarit, I.; Mattos, O. On the relation between adherence of a paint film and corrosion protection. *Electrochim. Acta* **1993**, *38*, 1999–2003. [CrossRef]