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Review

Corrosion Protection Systems and Fatigue Corrosion in Offshore Wind Structures: Current Status and Future Perspectives

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Abstract: Concerns over reducing CO_2 emissions associated with the burning of fossil fuels in combination with an increase in worldwide energy demands is leading to increased development of renewable energies such as wind. The installation of offshore wind power structures (OWS) is one of the most promising approaches for the production of renewable energy. However, corrosion and fatigue damage in marine and offshore environments are major causes of primary steel strength degradation in OWS. Corrosion can reduce the thickness of structural components which may lead towards fatigue crack initiation and buckling. These failure mechanisms affect tower service life and may result in catastrophic structural failure. Additionally, environmental pollution stemming from corrosion's by-products is possible. As a result, large financial investments are made yearly for both the prevention and recovery of these drawbacks. The corrosion rate of an OWS is dependent on different characteristics of attack which are influenced by access to oxygen and humidity. Structural degradation can occur due to chemical attack, abrasive action of waves, and microorganism attacks. Inspired by technological and scientific advances in recent years, the purpose of this paper is to discuss the current protective coating system technologies used to protect OWS as well as future perspectives.

Keywords: coatings; corrosion; wind energy; offshore wind platforms

1. Introduction

In 2000, wind energy contributed to meeting 2.4% of the EU's electricity demand. By 2015, this percentage raised to 11.4% [1]. A key objective of the EU's energy plan is to become the world leader in wind energy production by 2020 for onshore wind and by 2030 for offshore wind. To meet the EU's ambitions, it will be necessary to produce 265 GW of total wind power capacity, including 55 GW of offshore wind by 2030. The EU's energy plan has also targeted, in the near future, for 33% of total EU power to come from wind energy. This target can be reached by installing a total of 400 GW of wind energy capacity, consisting of 250 GW onshore and 150 GW offshore [2,3]. In order to meet 50% of the EU's electricity demands by 2050, a total of 600 GW of wind energy capacity will need to be reached consisting of 250 GW onshore and 350 GW offshore [3].

Table 1 shows that since 2011, the United Kingdom has the largest amount of installed offshore wind powered structures in Europe followed by Germany. Both countries have shown a significant increase between 2011 and 2015. Denmark is the third largest producer of offshore wind power, despite capping the number of offshore wind units in 2013. Finland, Ireland, Portugal and Norway's production levels remained unchanged for the same period. The slow implementation of offshore wind energy in Spain, according to Colmenar-Santos et al. [4], was due to environmental restrictions and depth characteristics off the coast of Spain which prevented the use of existing fixed-bottom technology structures. Furthermore, the non-existence of a stable regulatory frame-work in addition to a lack of government complementary measures promoting investment in this area were also factors mentioned by the authors [4].

Table 1. Offshore wind capacity installed—cumulative share by country for 2011–2015 according to the European Wind Energy Association (EWEA).

EU Member State	2011 [5] (MW)	2012 [6] (MW)	2013 [7] (MW)	2014 [8] (MW)	2015 [9] (MW)
Belgium	195	380	571	712	712
Denmark	857	921	1271	1271	1271
Finland	26	26	26	26	26
France	N/A	N/A	N/A	N/A	N/A
Germany	200	280	520	1049	3295
Ireland	25	25	25	25	25
Italy	N/A	N/A	N/A	N/A	N/A
Portugal	2	2	2	2	2
Norway	2	2	2	2	2
Spain	N/A	N/A	5	5	5
Sweden	164	164	212	212	202
Netherlands	246.8	246.8	247	247	427
United Kingdom	2094	2948	3681	4494	5061

This rapid development is not only due to the targets set by the EU, but also due to OWS units of larger capacity being deployed in larger farms [1]. Furthermore, Renewable UK states that: Offshore wind has become one of the most profitable renewable energy sources [10]. In 2015, Europe added a grid-connected capacity of 3 GW, almost twice the capacity added in 2014 [1,9].

Onshore wind farms have had an outstanding level of development in the last few decades; however, this has led to a decreased amount of available onshore sites remaining [4]. OWS have available physical space with deep ocean waters representing 70% of the world's area [11]. OWS can also be placed at greater distances from the coast to reduce visual onshore impact. Finally, OWS can be placed in locations where wind speeds are both higher and more reliable than onshore locations. Therefore, offshore wind energy is a promising option for clean energy generation in Europe.

It is difficult to compare the OWS developed in the early 2000s with structures developed post 2010. Project costs and subsidy support have both increased while capital grants are no longer available [12]. Project costs have increased due to a variety of reasons. For example, an OWS that is located 30 km further from shore and water depth that is 20 m greater could be associated with a project cost increases of 14% per megawatt (MW) [10]. The costs increase with the distance from shore and water depth and decreases with economies of scale. Economies of scale demand higher turbine numbers at further distances to enable a worthwhile cost reducing effect. The on-going development of offshore wind power has seen wind farm projects being developed further from shore and in deeper waters. Each new wind farm development increases the industry's knowledge and continues to push the boundaries of the technology, installation, operation and maintenance methods and financing. These developments have led to increasing costs higher than initially expected.

Currently, offshore wind structures are particularly abundant compared to other types of marine based devices such as waves or current energy converters [11]. There are two distinct types of offshore wind energy structures [13]; fixed [14] and floating [11,15–18]. Fixed platforms are primarily located in shallow waters. Floating platforms are installed in deep waters (typically more than 60 m) and further from shore than fixed structures [14]. Presently, the majority of offshore wind farms installed are fixed. Additionally, the highest percentage of the fixed structures are monopiles, followed by gravity based foundation and jackets [11]. Nevertheless, due to the availability of deep waters, there is strong evidence to suggest that the future of offshore wind will centre around floating structures, such as the WindFloat in Portugal [19–21]. There are a wide variety of technical developments in floating offshore wind. Three main design concepts have been pursued to date [11]: Semisubmersible platforms such as WindFloat [22], Tri-floater [23], WINDFLO [24], Vertiwind [25], WindSea [26]; tensioned leg platforms such as TLB [27], Diwet [28] and SOF [29]; and spar platforms such as Hywind [30], Njord [31], Sway [32] and FVAWT [33]. The future of these technologies will depend on their economic feasibility. According to S. Rodrigues et al. [12], commercial projects have higher installed capacities, are a highly capital intensive investment and are more complex to design mainly due to the higher number of turbines and longer distances to the shore.

OWS are subjected to several structural damage mechanisms such as corrosion [34–38], fatigue [38–54], thermal stress [1,55], wave and wind loading [1,56], fire and lightning strikes [3,4,57,58]. Corrosion and fatigue are the main mechanisms of deterioration of OWS. Adedipe et al. published a review focused on corrosion fatigue in OWS where the mean stress effects on fatigue crack growth as well as the influence of materials and test environments were discussed [38]. In sea water, an increase in stress ratio can influence crack growth (CG) rates regarding the interaction of the environment and loading frequency. The fatigue CG behaviour in weldments was found to be material dependent and influenced by the environment, loading conditions, microstructure, welding procedure and residual stresses [37].

The use of corrosion protection systems is essential to reach the expected service life for which a structure was designed. Different protection systems can be used to delay and mitigate corrosion initiation and its related consequences such as safety, structural integrity and service life. A passive approach to corrosion protection involves depositing a barrier layer that prevents contact of a material with the corrosive environment. Active approaches reduce the corrosion rate when the protective barrier is already damaged and corrosive agents come into contact with the metal substrate. Only the combination of both approaches can provide reliable protection against corrosion of metallic structures in harsh environments for the entire design life.

The application of coating systems is the most common method used to control corrosion. Coatings also offer a more pleasant visual appearance when compared to bare steel surfaces. The coating process involves the application of organic coatings, metallic coatings, or the combination of these two types (generally named as a *duplex system*) on the steel surface. The cost of coating onshore structures ranges 15–25 €/m^2 (depending on the structure, process and coating system) [37]. The cost of coating repair work performed on-site on offshore structures is approximately 5–10 times higher. When all job-related costs are accumulated, in offshore cases, the cost can increase to 1000 €/m^2, up to 50 times more than the initial application cost. Coating offshore is more expensive than onshore due to several factors including the logistics of transporting manpower and materials to the job site and limited access to the offshore structures due to weather conditions.

Moreover, achieving high quality results in an offshore environment is a major challenge. Corrosion on offshore structures is highly dependent on site-specific factors such as water temperature, salinity, chlorinity, water depth, and current speed. The application process and the specificity of the corrosion protection system are extremely important and should be suitable for the substrate and the environment. Effective, unambiguous, feasible and achievable specifications should be prepared by experts with a good understanding of the technology involved in protective coating systems. Expert judgment is primarily important when coatings systems are applied in very specific conditions such as harsh offshore environment.

Corrosion initiation of coated structures often occurs in areas where the coating was not properly applied or suffered mechanical damage during transport and installation. In offshore environments, the structures have long-term exposure to humidity with high salinity, intensive influence of UV light, wave action and bird droppings. Several studies have shown that bird droppings degrade the coating systems via chemical mechanisms [59–61]. Ramezanzadeh et al. [61] reported that biological materials can chemically influence the coating performance due to hydrolytic reactions as a result of catalytic effect of the enzymatic structure of bird droppings or pancreatin. This degradation provides conditions that allow corrosion initiation earlier than expected.

The corrosion rate of the steel tower of a wind platform is variable, based on access of both oxygen and humidity, influenced by the level of the water on the structure. Elevated salt concentration, mechanical load (e.g., ice drifts or floating objects), current speeds, biological stress, temperature variation, irregular inspection intervals, maintenance and repair costs, and design life should all be considered when planning the specification of a corrosion protection system. The following sections summarize the coatings systems and pre-treatment methods studied and applied on OWS from 2011 to 2016. The advantages and disadvantages of the most striking systems will be discussed as well as future perspectives. Additionally, the testing methods available, destructive and non-destructive, for degradation assessment (corrosion and fatigue) will be compared.

2. Offshore Wind Structures

An OWS typically consists of a station-keeping system, foundation, foundation/tower interface structure, tower, nacelle, rotor blades, and any other secondary steel structures such as boat landings, helipads, platforms, and walkways.

The foundation of the OWS can be either fixed or floating. A fixed turbine foundation is typically either a monopile, gravity based structure, or jacket type structure. A floating turbine foundation is typically a semisubmersible, tensioned leg platform, or spar. Aside from some gravity based structures which are typically composed of reinforced concrete, steel is the primary material used for all foundation types.

The foundation's structure is categorized into primary, secondary, and tertiary steel structural components based on their importance and function. Primary steel consists of structural components such as hull columns, trusses, main beams, and connection nodes whose performance is crucial to the overall integrity of the structure. The failure of a primary steel member could result in a catastrophic failure of the entire foundation. Secondary and tertiary steel items consist of all foundation elements whose performance is important, but whose failure will not result in a total collapse of the overall foundation structure (i.e., boat landing, walkways, pipe supports, etc.) All of the structural components of the foundation are exposed to harsh and complex stresses which include: corrosion, physical loads, biological attack, and mechanical damage. The environment is often characterized by violent winds, large waves, temperature changes, and infrared radiation, and ice and snow loads. These environmental factors directly impact the performance of surface protection systems such as coatings.

Offshore wind farms are typically planned for operational lives exceeding 20 years. Therefore, OWSs and their structural elements must be designed to meet or exceed the operational and environmental loads expected to occur during the design life of the farm, often in harsh marine environments (Table 2). OWSs are unique compared to other offshore structures in that they must be designed to resist the aerodynamic effects of the turbine coupled with the foundation motions due to wind and wave loading. The resulting structural dynamic responses of the wind turbine and support structures under the synergistic effects of wave and wind loading [38,54,62,63] must be considered when designing for ultimate strength, buckling, and fatigue based load cases. Table 2 indicates the requirements that OWSs must typically meet, however, requirements will vary based on the OWS project's classification society, client and operator, turbine provider, site location and metocean data, and design life. Examples of typical offshore standards can be found in DNV-OS-C401 [64], DNV-OS-J101 [65] and DNV-OS-J201 [66].

Table 2. Typical Requirements for offshore wind power structures (OWSs) [65,66].

Design Principles
• OWS should be designed to operate for stated design life without requirements for large-scale repairs, replacement, or refurbishment • OWS should be designed to resist mechanical damage, physical and environmental loads, and chemical deterioration while aiming to minimize the total cost of the structure
Design Principles
• Inspection, maintenance and repair should be performed on a schedule in compliance with industry standards and project specifications
• Structure and structural components should be designed with ductile resistance to applicable loads. Structure shall be designed to withstand all design load cases for strength and buckling design in addition to fatigue with the appropriate safety factors
• Structural connections should be designed as to minimize stress concentrations and complex stress flow patterns
Environmental and Operational Loads
The structure should be designed considering the loads listed below. Design load return periods may vary depending on the limit state, classification society, and client. Ultimate limit state environmental loads are typically based on a 50-year return period
• Wind loads
• Hydrodynamic loads induced by waves and current
• Tidal effects
• Marine growth • UV resistance
• Snow and ice loads • Temperature Loads • Mechanical Impact Loads (i.e., dropped object or boat impact)
Steel Grades
Steel materials shall be in accordance with the classification society and client standards. Steel quality and strength shall be appropriate to the criticality of the component. Steel components shall be classified according to their functional criticality and loading characteristics. Minimum yield strengths typically vary from 355 MPa for primary steel to 275 MPa for secondary and outfitting steel
The grade of steel to be used shall be selected considering there will be no risk of pitting damage
Corrosion Management
The structure's design should include a corrosion management system which shall protect the structure's materials against corrosion for the specified operating life, requires limited inspection, and meets all class and client specifications. Corrosion management plans typically utilize one or a combination of the following corrosion protection methods: coating, corrosion allowance, cathodic protection, or corrosion resistant materials. Any corrosion resistant materials should be specified by reference to a material standard (e.g., ASTM) where the requirements of the chemical composition, mechanical properties and quality control of manufacturing are defined [64]

2.1. Corrosion on OWS

The most probable failure and degradation mechanisms for steel structures are corrosion and fatigue. The tower and foundation of the OWS can experience a combination of these two mechanisms due to the coupled action of wind and wave loading in harsh environments [1,63,67]. Structural failure of an OWS may occur due to accelerated fatigue produced by an increase of stresses. Stresses can increase when natural frequencies are found to be similar to the rotor's frequency and can lead to devastating consequences.

Stress corrosion cracking is a major operational issue for OWSs [34] and is highly dependent on which zone the stress resides in (Figure 1). Four zones are usually considered in an OWS: *Submerged zone*—the zone where the structure is permanently submerged. Cathodic protection (CP) is generally used in this zone, often in conjunction with coating; *Tidal zone*—the zone between the minimum and the maximum level of tides and governed by their variations. This region is subjected to wetting and drying cycles. Degradation occurs due to chemical attack, abrasive action of waves and other substances in suspension (ice drift or floating objects) as well as the attack of microorganisms. This zone is often coated. *Splash zone*—the zone immediately above the maximum level of intertidal variation. In this zone the substrate is directly affected by water splash. The height of the splash zone is a function of the wave height, as well as of the speed and wind direction and is subjected to cycles of wetting and drying. This zone is often coated using a multi-layer scheme involving a glass flake polymer to help protect against mechanical damage. Corrosion becomes more significant as water evaporates and salts remain on the surface of the substrate.

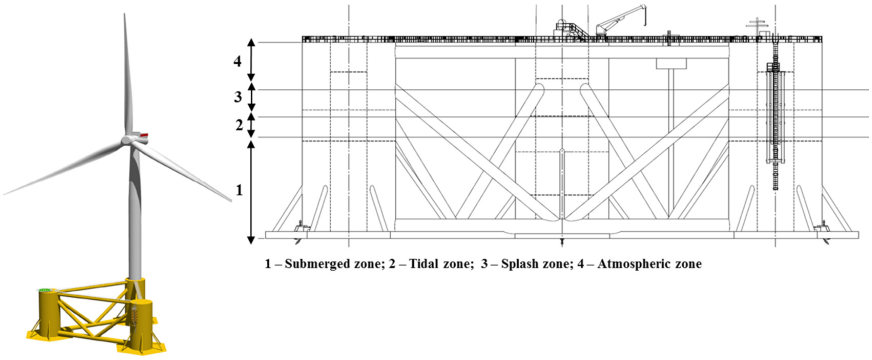


Figure 1. Structure and corrosion zones of Offshore WindFloat platform. Courtesy of PPI, Principle Power Inc. (Emeryville, CA, USA).

Atmospheric zone—the zone above the splash zone where the steel tower and topside structure suffers actions from marine aerosol, however, unlike the splash zone the structure is not directly attacked by water splashes. The winds carry the salts in the form of solid particles or as droplets of saline solution. The quantity of salt present decreases as a function of height distance from the mean water line. The wind speed and direction will influence the quantity of salt. This zone is typically coated.

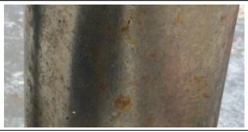
Corrosion can be classified according to the appearance of the corrosion damage or the mechanism of attack [68], namely:

- Uniform or general corrosion;
- Pitting corrosion;
- Crevice corrosion; filiform corrosion and poultice corrosion;
- Galvanic corrosion;
- Erosion-corrosion;
- Intergranular corrosion,
- Dealloying;
- Environmentally assisted cracking, including stress-corrosion cracking, corrosion fatigue and hydrogen damage.

Microbially Influenced Corrosion (MIC) is often seen as pitting attack [68,69]. MIC is associated with the presence of a great variety of organisms. Some can be easily observed such as barnacles, algae, mussels and clams while others are microscopic (bacteria). These microorganisms tend to attach to and grow on the surface of structural materials, resulting in the formation of a biological film or biofilm [68,69]. In the case of OWSs, heavy encrustations of hard-shelled fouling organisms form on the surface of the metallic structure (Figure 2). These organisms change the environmental variables including oxidizing power, temperature and concentration. Therefore, the value of a given parameter on the metallic/sea water interface under the biofilm can be different from that in the bulk electrolyte away from the interface. This difference may result in corrosion initiation under conditions in which there would be none if the film was not present. Presence of the biofilm may also yield changes in the form of corrosion (from uniform to localized) or an increase in the corrosion rate [68–70].

Two corrosivity categories must be considered for OWS according to ISO 12944-5:2007 [71]. Firstly, C5-M is for marine, coastal and offshore areas with high salinity for tidal, splash and atmospheric zones. Secondly, Im2 is for the zones permanently submerged in seawater. Corrosion rates for construction steel below sea level average 0.2 mm/year. In the tidal and splash zones, the corrosion rates may fluctuate between 0.4 to 1.2 mm/year [10,39]. Other authors have reported that the corrosion rate of construction steel in offshore environments can be as high as 2.5 mm/year depending on the location [72]. Table 3 shows examples of typical forms of corrosion that occur in marine environment on OWSs.

Table 3. Examples of typical forms of corrosion that occur in marine environment on metallic elements and structural components of OWSs.

Form of Corrosion	Description	Illustration
Uniform or general corrosion	Uniform corrosion on hot-dip galvanized steel components with significant section loss	
Pitting corrosion	Pitting corrosion in stainless steel piping components	
Crevice corrosion	Crevice corrosion in steel structural elements of flush mounted manhole with pooling water	
Galvanic corrosion	Galvanic corrosion on steel components in atmospheric zone due to improper material selection	
Stress-corrosion cracking (SCC)	Illustration of SCC	
Corrosion fatigue	Corrosion fatigue in steel components subject to cyclic loading	

Note: All images are courtesy of PPI, Principle Power Inc. (Emeryville, CA, USA).

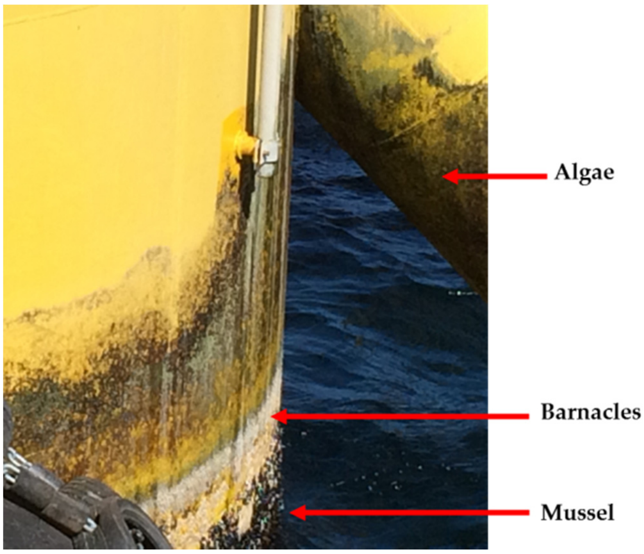


Figure 2. Floating OWS with encrustation of hard-shelled fouling organisms. Courtesy of PPI, Principle Power Inc. (Emeryville, CA, USA).

Fundamental corrosion protection measures for OWS include protective coatings and/or CP, corrosion allowance, inspection/monitoring systems, material and weld design decisions, and control of environment for internal zones [65,73]. Corrosion protection of an OWS, typically consists of two or three epoxy based coatings with a polyurethane (PU) top coat, however, this can vary according to exposure and location [35,62]. CP is commonly used in submerged and tidal areas; nevertheless, coating systems are also typically applied in these zones [65,73,74].

CP by sacrificial galvanic anodes for OWS is generally the preferential CP system used in industry nowadays. Impressed current cathodic protection (ICCP) is an alternative CP system option; however, it is uncommon today because it is more susceptible to environmental damage and third-party mechanical damage than galvanic anodes systems [65]. ICCP typically requires more maintenance and inspection which is costly to provide for un-manned OWSs. Also, there are currently no industry designs standards detailing requirements for impressed current systems as there currently are for the galvanic anode systems. Design considerations for impressed current systems were deleted from the scope of DNV-RP-B401 for the 2004 revision.

Table 4 shows the corrosion zones of an OWS, applicable methods for corrosion control [65] and the most likely forms of corrosion for each zone.

The implementation of an effective monitoring strategy for a structure allows both cost and safety benefits and OWS are no exception [1,75–77]. Within the civil engineering communities, the relevant subject concerning damage awareness is generally known as *Structural Health Monitoring* (SHM). SHM may be divided into *model-based SHM* and *data-based SHM* [77]. The *model-based SHM* is based on establishing a physical law-based model of the structure in its undamaged state. The data accumulated through time is used for conformity checking according to the model developed based on the undamaged structure. The inconsistencies and discrepancies found can be used to diagnose if and how the structure has changed through time. Alternatively, the data-based SHM uses techniques that analyse and recognize the pattern of the structures. This approach allows assessing the structural state considering the data measured form the structure without using any model as reference.

Table 4. Corrosion zones, methods for corrosion control and forms of corrosion in OWSs [65,66].

Corrosion Zones	Corrosion Control	Form of corrosion
Atmospheric Zone		
External and internal areas of steel structures	Coating systems	Uniform and erosion-corrosion, Stress corrosion cracking (SCC)
Internal surfaces without control of humidity	Corrosion allowance	Uniform and pitting corrosion, SCC
Internal surfaces of structural parts such as design of girders and columns	Corrosion allowance should be based on a corrosion rate ≥ 0.10 mm/year	
Critical components (e.g., bolting and other fastening devices)	Corrosion resistant materials are applicable such as stainless steel	Crevice, pitting and galvanic corrosion, SCC
Splash and Tidal Zones		
External and internal surfaces of steel structures	Coating systems	Uniform, crevice and pitting corrosion, MIC
Critical structures and components	Coatings systems combined with corrosion allowance.	
Internal surfaces of critical structures	Corrosion allowance and the use of coating systems is optional	Uniform, crevice and pitting corrosion
Structures and components below mean water level (MWL)	CP	
Structures and components below 1.0 m of the MWL	Coating systems	Uniform corrosion, MIC
External surfaces in the splash zone below MWL	CP	
Submerged Zone		
External surfaces of steel structures	CP, the use of coating systems is optional and these should be compatible with the CP	Uniform corrosion and erosion-corrosion, MIC
Internal surfaces of steel structures	CP or corrosion allowance (with or without coating systems in combination)	Uniform, crevice and pitting corrosion, MIC
Critical structures and components	Corrosion allowance should be based on a corrosion rate ≥ 0.10 mm/year. Marine growth (bacteria) may cause a mean corrosion rate ≥ 0.10 mm/year, and the application of a coating system should be considered	Uniform and/or pitting corrosion, MIC, SCC

Data-based approach to SHM is generally the most applied. The approach should be implemented considering a four stage procedure [75]:

1. Operational assessment;
2. Data acquisition;
3. Information selection and condensation;
4. Development of the statistical model.

In order for OWSs to withstand harsh offshore environments for design lives exceeding 20 years, adequate and planned inspection and maintenance must be performed. The scope of the inspection plan must include the entirety wind farm, including substations and submerged power cables. Detailed requirements and recommendations for inspection and maintenance of wind turbines, support structures, and submerged power cables should be performed according an offshore standard such as DNV-OS-J101 [65]. Recommendations and requirements for inspection of the substations are detailed in DNV-OS-J201 [66]. The substations in the OWSs are vital structures, and are commonly designed to a higher safety level than the other components. Similarly, a more thorough inspection is typically required for the substations than what is necessary for other components such as the wind turbines and their support structures.

Specific and detailed programs for the inspection of wind turbines and their support structures must be defined and implemented for each offshore wind farm project. Naturally, an inspection program for OWSs will depend on the number of structures in a wind farm, the type of foundation structure, and the specific environmental conditions for each site. For a single OWS or wind farms involving only a few OWSs, it is more reasonable to define rigid inspection programs with requirements for annual inspections and other periodical surveys covering all OWSs in the wind farm. For farms with large numbers of OWSs, rigid inspection programs are difficult to implement in a time efficient manner. In such cases, the inspection programs should be defined from a risk-based inspection planning approach and it is acceptable to perform inspections on a few representative OWSs [65,66].

2.2. Fatigue on OWS

Fatigue consists of a process of localized, cumulative and permanent damage resulting from the action of cyclic loading. Repeated loading and unloading of a member, primarily in tension, may eventually result in failure. This failure can occur even if the yield stress is never exceeded. The permanent action of cyclic loading can lead to failures such as crack initiation. Fatigue is a progressive failure in that further cyclic loading will lead to subsequent propagation. The crack propagation can ultimately lead to partial or complete failure of structural elements. Fatigue strength is primarily governed by the number of cycles of loading, the range of the service load stresses, and initial size of a flaw if it exists. Fatigue cracking often initiates in regions with high stress concentrations where the localized stress exceeds the yield strength of the material used or in areas where a discontinuity is more like to be found such as a weld or bolt hole.

Fatigue life is the expected service life of a structure under the application of the expected stress range, until failure occurs. The main parameters influencing the fatigue life of a structure are:

- Material properties—thermal and mechanical treatments, internal structure, internal defects of the metallic base, welding defects, mechanical properties (yield and tensile strength) and the presence of residual stress.
- Geometry and properties of the element—shape, size, stiffness, type and geometry of connections, shear-lag, fabrication and assembling errors, etc.
- Environmental effects—including the temperature and corrosion effects.
- Loading—tension and/or compression, bending, shear, torsion, multiaxial loading, stress range, average stress, etc.

Fatigue failure in OWSs often occurs due to the cyclic loading on the structure from harsh offshore environments. The constant action of wave and wind forces on the foundation coupled with the turbine loads often produce fatigue load cases which govern the design of the structure. Recently, Adedipe et al. [38] published a review of corrosion fatigue in offshore structures concerning the effects of mechanical loading, seawater and environment. Fatigue cracks can progress from pre-existing defects that may be introduced into structures during manufacturing, fabrication, transportation and installation. Welded structures are very susceptible to fatigue cracking. Common types of defects are described in standards such as BS 499-1:2009 [78] and EN ISO 5817:2014 [79]. The most common defects in welded joints (Figure 3) are cracks, undercut, and lack of fusion, lack of penetration, porosity and slag inclusions. These common defects are described below:

- Cracks are ruptures that generally occur in the weld or in the metallic base with slight apparent deformation. Three classes are generally recognized, namely: macro-fissure, cold and hot cracks;
- Undercut is a groove formed at the weld toe or weld root, or at the edge of a layer or a bead and it represents a stress concentration region. This problem is generally linked to the parameters of welding process and to poor execution.
- Lack of fusion is a discontinuity formed due to failure of fusion between the weld and the metallic base. This may occur due to the contamination of the surface or due to insufficient heating.
- Lack of penetration occurs when the weld metal fails to penetrate into the joint root due to inadequate joint design, improper electrode or low welding current.
- Porosity consists of the formation of cavities (discontinuities) due to gas entrapment during solidification of weld metal. Possible causes include lack of deoxidisers, high sulphur content of the metallic base, contamination of the surface and welding process parameters.
- Slag inclusions are non-metallic solid inclusions that are entrapped in the weld metal during welding. These, generally, arise from the composition of the materials used in the process of from the contamination of the weld metal. It may be minimized by suitable surface and groove preparation between successive steps.

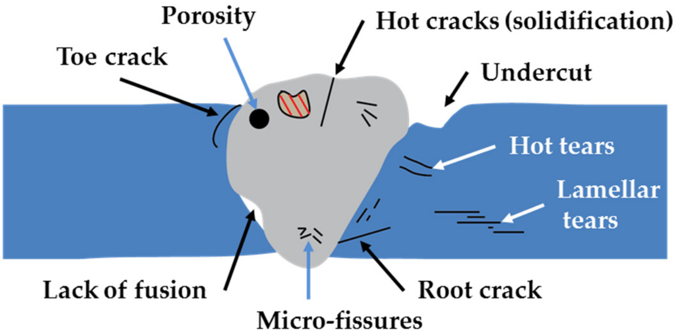


Figure 3. Schematic representation of typical weld defects (adapted from [80]).

Stress concentrations are linked to the fabrication process, geometry and design. Poor design can increase stress concentrations in a given region increasing its susceptibility to fatigue cracking. This becomes more important in cases of simultaneous actions of fatigue and corrosion [38,81,82]. In riveted or bolted structures, the stress concentration and residual stresses from the execution process are critical factors that influence the performance of the structure. Fatigue cracking in these cases often starts from micro-cracks around the holes, resulting from the operation of drilling or prompted by corrosion development. The typical causes for fatigue failure in bolted/riveted structures are [80–83]:

- Micro-cracks resulting from the riveting process;
- Overlapping of shear and bending at cross sections with changes in geometry;
- Thin connection plates;
- Non-symmetrical details;
- Poor structural design resulting in high stress concentrations;
- Corroded bearings or joints;
- Secondary stresses;
- Distortion, restraint, out-of-plane bending;
- Local stress concentration, reduced detail category and cut outs.

Welded joints are generally critical due to their susceptibility to stress concentration and residual stresses. Discontinuities linked to the execution of welding, particularly induced defects and heterogeneities in the microstructure. Therefore, welded joints are preferential areas for the development of fatigue cracking which is expressed in several types of cracking (Figure 2). The typical causes for fatigue failure in welded structures are:

- Poor weld or weld defects;
- Deficiency of fusion;
- Cold cracks;
- Vibration;
- Restraint;
- Geometrical changes;
- Repeated web buckling deformation.

After fatigue crack initiation, cyclic loading may further crack propagation into primary or secondary structural elements. Crack propagation is determined by the actual service load state of stress in the localized area. If not controlled, propagation can result into failure of the structural element with severe consequences to the safety of the structure. Collapse of the structure is a possibility when an unstable stage of the crack growth is reached in a critical area. For that reason, cracks or defects in OWS need to be reliably inspected and monitored to ensure that the structures meet the service design life. Cracks may derive restraint relief by propagating into low stress areas or, when possible, artificially creating a penetration to terminate the crack.

3. Coating Systems

Coating systems may integrate several layers of different types of coatings, however, the compatibility between the coats (layers) must be ensured. The coating process involves the application of non-metallic coatings, metallic coatings, or the combination of these two types of coatings on the steel surface. Metallic coatings are generally composed by non-ferrous metals, commonly zinc, aluminium and its alloys. Non-ferrous metals are more resistant to corrosion than carbon steel [84]. These metallic coatings provide protection to steel structures against corrosion by both galvanic action and barrier. Moreover, the metallic coatings protect steel sacrificially at damaged areas or at small pores in the coatings.

In the last few decades, several types of organic-based coatings have been developed [85], including anti-fouling paints [70,86–94], composites and nano-coatings [94–96], self-healing coatings [97–107], and hybrid sol-gel materials [98,108–121] among others. However, as far as the authors' knowledge, very few studies were performed on OWSs using self-healing and hybrid sol-gel coatings. This may be easily explained by the fact that these types of coatings are not well established in the market and the most are still under optimization studies. The scale of the technology readiness level (TRL) [122] is generally used to assign different processes and materials to their implementation ability and is based on a scale from 1 to 9 with 9 being the most advanced product/technology. Frei et al. [123] in 2013, reported that the TRL of most applications in self-healing topics is in classes 2 to 4. In material sciences, the TRL is at 4 (component and/or breadboard validation in laboratory environment) or 5 (component and/or breadboard validation in relevant environment) and in only few applications TRL was at 9 (successful operation in real-world application). Some of these coating systems with self-healing abilities show limitations to be applied in OWSs such as the high cost associated and the lack of experience in using these materials in OWSs.

The *ideal coating system* should assure the proper performance of the structure during its service life without requiring structural repairs. The major factors to be considered in the selection of a coating system are: the type of structure and its importance, environmental conditions, service life, required durability, coating performance, and costs including its application and surface preparation. For a coating system to achieve the optimum performance, the following steps should be followed [124]:

- Selection of the most suitable protective system according to the particular environmental conditions;
- Coating requirements;
- Assessment of the structure design to optimize coating system application;
- Detail clearly and unequivocally the specifications of the system;
- Use adequate and suitable techniques for coating deposition;
- Respect the requirements of the coating system;
- Rigorous quality control of the specified and supplied materials;
- Inspection at all phases during coating system application.

For OWS, in particular, additional aspects should be considered. The coatings should be resistant to high corrosive stress due to elevated salt concentration in both water and air, impact loading due to ice drift or floating objects, biological stress, namely under water, notable variations in temperature of both water and air [35]. Algae (plants), animal and bacteria life on site causes biological stress on the structural components in the submerged and in the splash zones. Algae and animal growth adds weight to the structural component and influences the geometry and the surface texture of the component. The marine growth may therefore impact on the hydrodynamic loads, the dynamic response, the accessibility and the corrosion rate of the structure.

Inspections, at all phases, are essential to make sure that all requirements of the coatings specification are satisfied. An unambiguous and adequate quality control system should be implemented. Quality control of the entire coating process will ensure that the applied systems will reach their full potential. Protection of steel by painting is generally ensured by the application of several coats of different paints, each having a specific role. The different types of coats are defined by the order of application on the substrate, namely: The primer (first coat), undercoat (any coat between the primer and the finishing coat) and the topcoat (finishing coat). The different layers should have different colours to ease its identification. Generally, the coating system is characterized by the number of layers (coats) involved and is known by the name of the paint binder used in the topcoat. There are also systems without undercoats. In recent years, new systems of paints have been developed in which the anticorrosive function and other required properties are ensured by the same paint, thus reducing the number of coats applied and the costs associated with its application [125–129]. An important parameter to characterize the coating protection capacity is adhesion strength between coating system and substrate as well as the adhesion between coating layers.

Inadequate adhesion may promote failure of the coating and expose the substrate to the environment (aggressive species) and therefore cause corrosion. Most organic-based coating failures such as cracking, delamination, fouling damage, mudcracking and dirt under paint can only be resolved by sandblasting the surface or removing the coating mechanically, cleaning the surface and applying a new coat. In case of fouling damage, the damaged paint should be replaced by a tougher and more adherent coating with antifouling properties [68]. The primer that is applied on the steel surface should provide adequate adhesion and anticorrosive protection. Two main categories of primers are defined considering the type of pigment used by ISO 12944-5:2007 [71], namely zinc-rich primers and other primers. Zinc-rich primers contain zinc dust pigment with a percentage equal to or higher than 80% in the non-volatile portion. Zinc dust pigment should be in accordance with standards such as BS EN ISO 3549:2002 [130] or ASTM D520-00(2011) [131]. The other primers contain zinc phosphate pigment or other anticorrosive pigments with a percentage lower than 80% in the non-volatile portion. Due to health and environment concerns restrictions on the use of zinc chromate, red lead and calcium plumbates were implemented.

Undercoats are generally used to increase the overall thickness of the coating system. The top coat protects the layers below from environmental agents such as UV light from the sun and provides primary abrasion resistance and decoration when necessary [132]. EN ISO 12944-6:2007 [71] lists some paint systems and for purposes of application paints can be classified as solvent-borne, water-borne or solvent-free. Coatings are partially categorized according to the type of drying and/or curing in addition to being reversible or irreversible [71]. These are further subdivided by the generic type of binder (Table 5).

Table 5. Classification of paint coating types according to EN ISO 12944-5:2007 [71].

Paint Coating Types Classification		**Typical Examples**	**Typical Binders**
Irreversible coatings	Air-drying paints (oxidative curing)	–	Epoxy ester Alkyd Urethane alkyd
	Water-borne paints (single pack)	– – –	Polyurethane resins (PU) Acrylic polymers Vinyl polymers
	Chemically curing paints	Epoxy paints (two-pack)	Epoxy Epoxy vinyl/epoxy acrylic Epoxy combinations
		Polyurethane paints (two-pack)	Polyester Acrylic Fluoro resin Polyether Polyurethane combinations
	Moisture-curing paints	– – –	Ethyl silicate (one-pack) Ethyl silicate (two-pack) Polyurethane (one-pack)
Reversible coatings	– – –	– – –	Chlorinated rubber Vinyl chloride copolymers Acrylic polymers

Irreversible coatings can be classified according to Table 5 [71]. Air drying paints are a two-step process for film formation. Firstly, the layer is formed by solvent evaporation. Then the binder mixture reacts with the oxygen from the air to cure and harden further. Air dry coatings first go through a short time of an evaporation stage to lower the percentage of carrier in the film which allows exposing more of the binder to the air. Afterwards, the oxidation begins as the residual components start to react with oxygen in the atmosphere. In alkyd coatings, the alkyd resin and drier additives in the formulation initiate the chemical crosslinking with each other once exposed to oxygen, forming a layer. The layer formation and the curing process may extend from a few hours to days. The coating will continue to oxidize during the lifetime of the coating. This continuous crosslinking is the reason why old alkyd based paint becomes brittle.

Reversible coatings' layers are formed by solvent evaporation and it is feasible the re-dissolution of the layer occurs in the original solvent. In irreversible coatings, the layer also dries by solvent evaporation (if present) followed by a chemical reaction (or coalescence in case of water-borne paints). The process is irreversible; therefore, the layer cannot be dissolved in the original solvent or in a suitable one.

Appropriate surface preparation is crucial for the performance of paint systems. In certain cases, surface preparation is very expensive and/or difficult to carry out leading to the development of coatings known as *surface-tolerant* [133–135]. This type of system consists of introducing hydrophilic solvents or surface-active agents in the coating that when combined with the moisture on the surface will cause moisture dispersion through the film paint. Nevertheless, this type of coatings should only be used as last resort.

EN ISO 12944-1:1998 [136] defines the durability of a coating system as *the expected life, in years, before first major maintenance*. The durability of a coating system depends on several parameters such as: type of coating system, the condition of the substrate, the design of the structure, the quality of surface preparation, the application procedure, its control and conditions of application, and the exposure conditions. Usually, increasing the number of layers and the total dry film thickness will increase the durability of the coating system. Higher durability is also provided by selecting a suitable system for a corrosivity category superior than the one predicted.

3.1. Coating Systems for OWS

The selection of coating systems for OWSs is not a forthright matter. The approach for coating system selection for OWSs is similar to that for other offshore structures designed for oil and gas production.

In order to meet the objectives of the European wind industry for offshore wind by 2030, it is necessary to decrease OWS costs and increase the output and reliability of current wind energy system technologies. Recently, Wang et al. [1] reported a comprehensive review of Structural Health Monitoring Systems (SHMS) for OWS. The authors concluded that the optimization of SHMS will lead to reducing labour costs of wind turbine inspection by the prevention of unnecessary replacement of components or early repairing interventions such as repainting of affected components. Analysing coating design weaknesses before failure will contribute towards the strategic policy objectives of Europe 2020.

A classic system that meets the corrosivity categories C5-M and Im2 would include a zinc-rich, epoxy-based primer coating (thickness of 60 μm), three successive epoxy midcoats, and one PU topcoat. The total nominal dry film should have a thickness of 400 μm. This selection process considers only organic coating systems and does not include the detailed application of metal coatings, which are quite usual on OWS [35]. The typical coating systems, applied on traditional OWS, are specified in ISO 20340:2009 [137] and hot-dip galvanized (HDGS) and metallized steel substrates are included for specific purposes. Previous systems mostly consisted of a Zn/Al-metallization, organic pore filler, several intermediate epoxy-based coats and a PU based topcoat [35] with a typical total dry film thickness of about 400 μm. Table 6 shows the number of layers, the total dry film thickness and the type of primer used according to each standard [138].

Generally, chemical resistant coatings should be selected such as urethanes, epoxies, chlorinated rubber and vinyl polymers. As experience is gained at a particular location, changes are made accordingly in the coating system. Table 7 indicates typical systems that may be used according to exposure of OWSs.

Table 6. Number of layers, total dry film thickness and type of primer used according to each standard and to exposure of OWSs.

Primers According to Exposure Zone	Number of Layers	Total Dry Film Thickness/μm	Standard
Atmospheric Exposure			
EP, PU	3–5	320	EN ISO 12944 [71]
	2	500	
EP, PU (Zn rich)	4–5	320	
EP (Zn rich)	≥3	>280	ISO 20340 [137]
EP	≥3	>350	–
EP (Zn rich)	≥3	>280	NORSOK M-501 [138]
EP	≥2	>1000	
Underwater and Splash Zones			
EP (Zn rich)	3–5	540	EN ISO 12944 [71]
EP, PU	1–3	600	
EP	1	800	
EP, PU (Zn rich)	≥3	>450	ISO 20340 [137]
EP, PU	≥3	>450	–
EP	≥2	>600	–
EP	≥2	≥350 [a]	NORSOK M-501 [138]

[a] The coating system must be used simultaneously with CP.

Table 7. Type of coating systems typically used according to exposure zone of OWSs.

Atmospheric Exposure
Vinyl system (3–4 layers) Zn phosphate pigmented two-pack epoxy primer (1 layer) Two-pack epoxy (2 layers) Inorganic zinc silicate primer (1 layer) Two-pack epoxy (2 layers)
Chlorinated rubber system (3–4 layers)
Underwater
The main control is CP. The use of coating systems is optional, generally EP based coatings, and these should be compatible with the CP. When coatings are used fewer anodes are necessary and the corrosion protection system is expected to last longer
Splash and Tidal Zones
Coatings similar to those for the atmospheric zone are used. Higher film thickness is employed
The steel thickness is increased (to act as corrosion allowance) and is coated with the same coating system of the rest of the structure
Thick rubber or neoprene coating up to 15 mm of thickness
Polymeric resins or glass-flake reinforced polyester material are often used to protect against mechanical damage

OWS require resilient coatings able to withstand enormous stress, including the impact of rain and hail drops on blades at tip speeds up to 300–500 km/h. The top coating companies servicing the offshore wind sector include Hempel, Jotun and AkzoNobel. These companies are also major global suppliers of marine coatings. There are several niche players focused on specialist coatings, specifically for new-generation rotor blades. Companies such as BASF and Bayer Material Science aim to be suppliers of a broad array of materials, including coatings, for wind turbines [139]. Papers devoted to discussing surface layer protection for wind turbine rotor blades [140] and thermal spray coatings in renewable energy applications [141] were published. Nevertheless, few studies focused on testing coating systems for corrosion protection on-site and fatigue corrosion of OWS have been published after 2010. These papers are shown in Table 8.

Repairing the coating of structures in offshore environments can be very difficult, expensive, and are likely to be contaminated with chloride ions during the repairing procedure. Therefore, studies on the corrosion resistance of a paint system on steel substrate contaminated should be considered. Nevertheless, only one publication was found since 2010. Shi et al. [142] reported in 2011 (Table 8) a study on the influence of salts deposition in offshore atmosphere (typical oceanic climate of a tropical zone) at the steel/paint interface of zinc-rich paints on steel substrate. The authors found the formation of layers of corrosion products under the paint. The electrochemical results indicated that the time duration of the CP of contaminated substrate was much shorter when compared with the substrate without any contamination. It was suggested that the exposure time of steel substrate before paint application should be as short as possible to avoid degradation due to saline deposit [142].

In early 2016, six organic coating systems were investigated according to their performance under Arctic offshore conditions [143,144]. The studied coating systems were organic which differed in coating material, hardener, number of layers, dry film thickness and application method. The generic types studied were epoxy and polyurethane with different hardeners. In the epoxy type the hardeners tested were polyamine, phenalkamine and amine. In the polyurethane type the hardeners tested were aliphatic, moisture-hardener and isocyanate. The authors assessed the corrosion performance of the coatings, tested the coatings adhesion, performed hoarfrost accretion measurements, resistance, abrasion and wettability tests. The test conditions were adapted to Arctic offshore conditions covering low temperatures down to −60 °C [143,144]. The results indicated that if exposed to very low temperatures, the coatings change their response to corrosive and mechanical impact loads. The corrosion protection resistance dropped and the coating adhesion in terms of pull-off strength increased. The impact resistance and abrasion resistance dropped. Wettability in terms of static contact angle and surface energy is independent of the coating type. Hoarfrost accretion changes with coating type. Nevertheless, no trends were established to roughness or wettability parameters. Improved behaviour was obtained for a three-layer system with high thickness (1400 µm), consisting of two glass-flake reinforced epoxy coats and a polyurethane topcoat [143,144]. Momber, also in 2016 [74], reported a study about the assessment of deterioration of protective coatings and exposed steel surfaces on offshore wind power platforms in the North Sea and the Baltic Sea. A procedure for the assessment of coating deterioration and weight loss on exposed steel surfaces was also proposed. The majority of coating damages was attributed to inappropriate design and to mechanical loading. Colour-based digital image processing was applied for the quantitative recording and rating of coating deterioration processes. Preliminary investigations revealed that colour-based digital image processing opens the opportunity to evaluate fouling, top coat colour changes, and early iron corrosion products [74]. Wind turbine blades (WTB) are generally protected by elastomeric materials in forms of tape. These must be maintained or replaced. Tests and real life experience indicate that they do not provide adequate protection during the entire lifetime of the WTB. These materials are generally based on PU. Research efforts are focused in continuous development of new durable tape materials pursuing a product that can withstand the harsher environmental exposure, increasing loads and increasing stresses [145,146]. Valaker et al. have shown that the inspection of the industrial erosion protection coating exhibited craters [146] which were explained by the trapped air bubbles in the coating during mixture of the two components. The authors reported that the industrial erosion protection tape did not fulfil the requirements needed to study the erosion resistance on a sufficient level that would provide an acceptable assessment. The adhesion between the test samples and the tape failed before signs of erosion could be observed. In the end, the authors also reported that the polymer itself was believed to have good erosion resistance [146].

3.2. Application Methods

Coating systems may be applied either in factory or in situ. Coating application in factory offers several advantages such as superior control of application conditions to ensure superior performance, ease of damage repair, as well as superior waste and pollution control. Nonetheless, disadvantages should also be taken into account such as the limitation of the component size as well as the possibility of inducing damages during handling, transport and erection. The maintenance works are generally carried out in situ. During these procedures, the weather conditions should always be taken into account.

3.2.1. Organic Coatings (Paints)

The application methods commonly used to coat construction steelwork with organic based coating systems will be discussed. The most common coating application methods for constructional steelwork are manual and spraying. Manual coating application can be accomplished by brushing and/or rolling; however, it depends on the geometry of the substrate to be coated. The most commonly used spraying methods are air spray, low-pressure airspray, airless spraying, and air assisted airless spray, and electrostatic spray [147]. All the properties concerning the method of application, e.g., paint viscosity, spraying pressure, spraying angle, type of nozzle and surface distance should be selected in order to obtain a uniform and continuous coating. Other methods such as dipping, flow or roll coating, and doctor blading may also be used for constructional steelwork however, generally are only used for special components or for plastic coatings [84]. Application by dipping is a simple method. The metallic substrate is dipped into a tank containing the coating or in some cases the tank is raised to cover the stationary steelwork. Coatings must be specifically formulated with adequate thinning for the dipping method [84]. Additionally, on the lower parts of the coated steelwork there is a tendency for the appearance of defects such as "drips" and "tears" and the edges tend to be coated with lower thickness than the main surfaces. The dipping method is not suitable for all types of coatings and there are limitations on the size of steelwork that can be treated due to the size of the tank and the amount of handling required. The main advantages are that all parts of the steelwork (internal and external surfaces) are coated in one step, it is a quick method and skilled operators are not necessary.

The main comparison metric among the common methods of coating application on construction steelwork may be based on the speed of application. The average application area with one layer of coating per day and per operator, for the different coating application methods, is significantly dissimilar (Table 9). The rate of application is clearly superior for airless spray method. The method with the lowest application speed is the brush method, however, in many situations, such as in small complex geometries, it is the most effective one. Additionally, the loss of paint and masking by over spray are avoided by using brushing. Roller coating is generally limited to large and flat surfaces.

Overall, spraying is the fastest and the most employed method for coating constructional steelwork [84]. According to Bayliss and Deacon [124] the comparative costs of coating application for airless spray, air spray, roller and brush are respectively 1:2:3:4. The paint losses in application are approximately 30% for air sprays and 5% for rollers and brushes. The application cost is also influenced by the type of coating (Table 6). Alkyd based coatings are generally less expensive (15%–20%) to apply than two-pack coatings.

Table 8. Published papers between 2010–2016 regarding corrosion protection systems and fatigue corrosion.

Year	Study	Results and Conclusions	Reference
2010	The various coating systems used on OWS were discussed. Guidance on minimizing potential problems related to the design and fabrication of OWS was also given	The steel builder, paint applicator, and paint supplier are all responsible for the success of the corrosion protection of OWS. Therefore, they must work closely together to achieve the best results	[37]
2011	Review on corrosion and corrosion protection of OWS	The types of corrosion and corrosion phenomena were summarized. Practical solutions for corrosion protection of OWS, were discussed	[34]
	The corrosion behaviour of an epoxy zinc-rich paint on interface-contaminated carbon manganese-silicon steel was studied	The results indicated that the Zn corrosion products grew from the surface to the inner of the paint. Salts contamination promoted the growth at locations close to the steel/paint interface. EIS results show that the corrosion resistance of the contaminated paint was significantly influenced by diffusion of Zn corrosion products during the initial stage of immersion, and diffusion of Fe corrosion products at the end of immersion	[142,148]
2015	Droplet erosion protection coatings based on PU matrix were proposed, tested and compared with industrial solutions	Two of the coatings were reinforced with particles to investigate if this would improve the erosion resistance in the coating. The weighing after erosion testing clearly revealed significant differences in the erosion resistance. All coatings, except one, showed clear sign of material loss just after short test duration. The industrial coating showed sign of failure even more often and earlier than all the purposed coatings. One of the proposals showed such good results that it is further discussed as a potential world leading surface treatment for wind turbine blade tips	[146]
2015	Six corrosion protection systems for OWS have been tested on-site for three years in the North Sea. Three different exposure zones, (splash, IZ and UWZ)	The systems included single- and multi-layered organic coatings, metal-spray coatings, and duplex coatings. The duplex systems, consisting of Zn/Al spray metallization, intermediate particle-reinforced EP coating, and PU top layer, showed superior corrosion behaviour. Mechanical damage to the coatings initiated coating delamination and substrate corrosion. Flange connections were found to be critical structural parts in the splash zone in terms of corrosion. Except for one coating system, welds have been protected well. Coating integrity on difficult-to-coat structural parts was satisfactory for all systems	[62]
2015	Review of the current standards and guidelines on corrosion protection of offshore wind foundations and experiences reported within the industry over the last decade, during which time offshore wind has gone from a marginal industry to a major governmentally supported renewable energy source within Northern Europe in particular	The authors highlighted areas in which the most frequently used standards and guidelines for corrosion protection of OWS are in need of updates and details where more work is needed in order to provide more documentation on actual conditions. Project cost reductions have also been discussed. The major challenges connected to the corrosion protection of offshore monopile wind foundations were also identified. (Localized corrosion; Fatigue and hydrogen induced stress cracking; clarifying the CP design, externally and internally, monitoring of internal CP and Offshore coating repairs)	[149,150]
2016	Coating adhesion in terms of pull-off strength and fracture mode was assessed on coatings in the underwater and intermediate zones. The coating systems included organic coatings and duplex coatings	Corrosion protection coating systems for offshore wind power constructions were subjected to offshore conditions on a test site in the North Sea for three years in order to evaluate their protection performance. All samples met the requirements for offshore ageing in terms of adhesion. An adhesion-based "corrosion protection effect" (CE) is introduced and calculated for the coating systems	[36]

Table 9. Comparison of coating application methods (adapted from [84]).

Application Method	Area Covered per Day and per Operator (one Layer of Coating)	Advantages
Brush	100 m^2	Cheap; Requires no expensive equipment; Allows painting crevices and other difficult areas
Roller	200–400 m^2	Rates up to four times faster than those achieved with brushes; Suitable for coverage rather than controlled painting
Airspray	400–800 m^2	Low cost and higher safety hazard when compared to airless spray
Airless spray	800–1200 m^2	Higher output, less paint fog, less overspray and minimum rebound when compared to airspray

3.2.2. Metallic Coatings

The most common methods used for application of metallic coatings are hot-dipping, electroplating, thermal spraying and diffusion. Generally, hot-dipping and spraying are employed for structural sections. For components and smaller pieces, electrodeposition, diffusion and hot-dipping are used.

Hot dip galvanizing is the most important zinc coating process [151,152]. A coating of zinc and/or zinc-iron alloys on iron and steel elements is formed by dipping the substrate in a molten zinc bath at a temperature of ≈450 °C. When the metallurgical reaction is completed (Figure 4), approximately 4–5 min, the substrate is withdrawn [151–153]. EN ISO 14713-1:2009 [154] provides guidance on the general principles of design and corrosion resistance for protection of iron and steel with zinc coatings. Specific recommendations for hot-dip galvanization are given by EN ISO 14713-2:2009 [153]. This standard provides guidance regarding the effects of steel composition in hot-dip galvanizing coating properties since certain elements such as silicon and phosphorous may affect the process. To produce high quality zinc coatings a good surface preparation must be performed. The surface treatment process prior to hot dip galvanization may include organic-solvent degreasing and cleaning, alkaline degreasing, acid pickling and abrasive blasting. These methods and processes are specified by ISO 27831-1:2008 [155]. According to EN ISO 1461:2009, visually inspected surfaces should be free of nodules, roughness, blisters and uncoated areas. Those who fail visual inspection should be re-galvanized. The zinc coating thickness is specified by EN ISO 1461:2009 or by relevant standards according to the type of product.

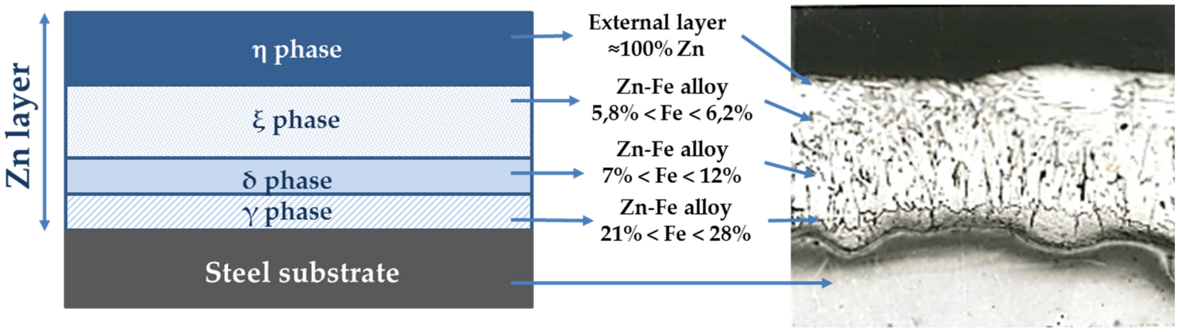


Figure 4. Microstructure and intermetallic layers with the respective content of Fe in hot-dip galvanized steel (HDGS) (adapted from [152]).

Electroplating, also known as electrodeposition is used to apply different metals to metallic substrates for corrosion protection [84]. For constructional steelwork, zinc is the most common metal applied. The general requirements and methods for electrodeposited coatings are indicated in BS EN

1403:1998 [156]. The particular requirements for electroplated coatings of zinc with supplementary treatments are given by BS EN ISO 2081:2008 [157].

Thermal spraying process involves heating the surface of metallic materials, until achieving a molten state, and then propelling them on a metallic surface by flame or arc spraying. The thermal spraying processes and classification according to the type of spray material, energy carriers and operation are described in BS EN 657:2005 [158]. Thermal sprayed particles adhere to the surface by physical processes, although fusion or diffusion bonding can be achieved by suitable heat treatments. The quality of the coating is mainly characterized by its structure, and distribution and size of phases, pores, oxides and inclusions. Thermal spraying avoids distortion and structural changes of the substrate if the coatings are not thermally post-treated; the component size is not a limitation; allows coating components with complex design; allows the application of different coating thicknesses in the same substrate and can be used for site application. However, the bond strength of coatings without thermal post-treatment is exclusively from adhesive forces; micro porosity and higher residual stresses in thick coatings. The guidelines for producing thermal spraying coatings are described in BS EN 14616:2004 [159]. ISO 2063:2005 [160] applies particularly to thermal spraying metal coatings of zinc, aluminium or their alloys for protection of iron and steel against corrosion. Thermal spraying should be performed after surface preparation (clean, dry and not oxidized). BS EN 13507:2010 [161] specifies the pre-treatments for thermal spraying.

Some coatings are produced by diffusion process in which the coating metal, usually in the form of powder, reacts with steel at a temperature below the melting point of the metal. The process for producing zinc diffusion coatings is known as sherardizing [84]. ISO 14713-3:2009 [162] specifies the principles of design that are appropriated for sherardized coatings, such as the fact that the welds should be performed before sherardizing. The coating thickness is controlled by the amount of zinc dust and by the temperature and processing time. Three classes of sherardized coatings are specified by BS EN 13811:2003 [163]. According to the given guidance the class 45 is suitable for highly corrosive environments. Further guidance on the coating thickness of zinc coated materials for use in environments with different corrosivity categories is given in EN ISO 14713-3:2009 [162]. The materials should be inspected considering the sampling for testing specified in BS EN 13811:2003 [163] or the procedures selected from ISO 2859 parts 1:1999 [164] and 3:2005 [165]. According to EN 13811:2003 [163], the coating thickness should be determined by magnetic method considering the guidelines in EN ISO 2178:2016 [166] or by the gravimetric method according to BS EN ISO 1460:1995 [167]. Microscopic cross-section method may also be used, although, it may not be appropriate for routine inspections due to time constraints.

3.3. Procedures—Previous Assessment, Selection of Coating Systems and Specifications

Suitable specifications are essential to ensure effective corrosion protection by paint/coating systems. According to EN ISO 12944:1998 [136] several specifications should be considered, namely:

- Corrosivity of the environment—should be analysed in order to establish the specific conditions and stresses which may affect the selection of the coating system;
- Structure—should be previously examined and its design should be optimized;
- Condition of the surface—should be assessed;
- Coating system identification and selection for the required durability considering the environment and the method of surface preparation to be used;
- Minimize the risks of harmful effects to the environment, health and safety;
- Work plan where the application method is established;
- Inspection and maintenance plans—these should cover the whole service life of the structure.

The corrosivity of the environment is classified according to EN ISO 12944-2:1998 [168]. The selection of a coating system must take in consideration the type of environment and the location of the structure. During the design phase, the preparation of the inspection and maintenance plans should be based on the expected durability of the coating system.

However, the maintenance plans may be changed if the structure operation and/or the environmental category changes or in case of emerging new materials and/or technologies. The accessibility, general requirements for maintenance and costs are likewise important factors regarding the selection of a coating system. If the access is difficult and expensive, such as in OWSs, the coating system must provide increased durability. Preference should be given to coatings that do not require complex procedures and facilities for application. The costs comprise of the application costs (initial costs) and the maintenance costs during the design life of the structure. The selection of a coating system for corrosion protection should be performed considering the advantages and disadvantages of organic and metallic coatings. Table 10 shows a comparison between organic-based coatings (paints) and metallic coatings.

Table 10. Comparison of application methods for organic-based and metallic coatings (adapted from [84]).

Advantages	Disadvantages
Organic-Based Coatings (Paints)	
Application is, generally, straightforward	Application is prone to many mistakes due to poor workmanship
Easy to apply different types of coats on the substrate	
No limitations on the size or type of structure	The expected life is difficult to predict even when standards and specifications are available
Good resistance to acidic conditions. Fulfil many requirements due to a wide range of materials	
Metallic Coatings	
Controlled application	If further painting is required, painting of a metallic coating is in general more difficult
Available standards for specification, higher level of certainty of performance	The size of fabricated steel items and the availability of an appropriate galvanization plant are limited in hot dip galvanization
Durability is easy to predict and premature failure rarely occurs	Without additional protection, metallic coatings, generally, develop unpleasant appearance through the time
Higher resistance to damage and easier handling	
Abrasion resistance is approximately 10 times or more than the conventional paint systems	If welding is carried out after the application of the metal coating or when severe damage occurs, it is difficult to accomplish the same standard of protection in those areas compared to the rest of the structure
In case of damage, corrosion attacks preferentially the metallic coating instead of the structural steel	
Thick coating is possible on edges	

3.4. Surface Preparation

The main objective of steel surface preparation is to remove any corrosion products and other contaminants. The state of the surface prior to coating is one of the most significant factors in determining the performance of protective films. Coatings may fail prematurely if applied on surfaces that have not been cleaned adequately. The surface preparation is therefore extremely important to ensure the high level of adhesion on the substrate surface in order to achieve the full protective potential of the coating. The surfaces to be treated should be well illuminated and accessible. The environmental conditions on site should be checked in order to comply with the requirements provided by the paint manufacturer. The performance of a coating is highly influenced by its ability to adhere properly to the material to which is applied. Careful attention must be given to the steel preparation, namely to edges, corners, weld seams and surface imperfections. Generally, the surface to be coated must be cleaned of dust and dirt, grease and moisture. Corrosion products and other contaminants should be removed to ensure coating adhesion to the substrate. Poor adhesion may cause peeling or detachment and therefore compromise the corrosion resistance of the substrate.

The most effective adhesion between a coating layer and a substrate is provided by a chemical bond. Representative examples of such type of interactions are the ones stablished between the zinc layer and the steel in hot-dip galvanized steel (HDGS) (Figure 4) [152]. Nevertheless, most of the organic coatings establish a polar adhesion reinforced by mechanical adhesion. Mechanical adhesion is promoted by surface roughening in addition to the cleanliness and stability of the substrate [124]. Thus, the performance of coatings depends on the surface conditions of the substrate prior coating application.

EN ISO 12944-4:1998 [169] describes several methods for surface preparation. Three categories for surface cleaning are considered: water, solvent and chemical cleaning; mechanical cleaning including blast-cleaning; and flame cleaning. Some of these methods are specified by EN ISO 8504 [170].

3.5. Execution Conditions

The methods for application of coating systems as well as guidance for carrying out paint work are described in EN ISO 12944-7:1998 [147]. According to this standard, there are some pre-conditions required for the execution of coating/paint work:

- Technical qualification of personnel;
- Achievement of the quality level specified in each stage;
- Substrate requirements;
- Compliance with all health safety and environmental policies.

Upon delivery of the coating and during application, the condition of the paint should be checked in order to ensure the conformity of the container label with the specified product description [147]. The supplied coating materials should not be applied at temperatures below 3 °C and above 30 °C, unless other temperatures are indicated by the manufacturer. The shelf time (i.e., storage time) should also be provided by the manufacturer and adhered to. The coating materials should not be applied at temperatures less than 3 °C above the dew point [147], which is determined according to BS EN ISO 8502-4:2000 [171].

The moisture content of the air influences the painting operations and is indicated by the relative humidity at a particular temperature. Relative humidity is important during paint application since the amount of moisture in the air and temperature of the steel surface may lead to condensation on the steel surface leading to adhesion problems with some coatings. Other coatings are sensitive to humidity during their curing. For instance, the surface of amine cured epoxy based coatings will be affected by high humidity conditions. Such coatings can develop a surface oiliness, exudate, or whitish spots variously referred to as *amine-blush*, *sweating*, or *bloom* [172]. Other such as some zinc silicate coatings will not cure completely under low humidity conditions. The relative humidity conditions applicable to various coatings should be provided by the manufacturer.

3.6. Quality Control

The quality control of a coating application includes the following steps: (i) Surface preparation; (ii) Coating material and its application procedures; (iii) Environmental conditions during working procedures and (iv) Supervision and certification of the procedures implemented during coating application.

The specifications of a coating system should be prepared by manufacturers and suppliers with a proper understanding of the technology involved. These specifications should be effective, feasible, unambiguous and achievable. This judgement is particularly crucial when the protective system is applied on structural elements exposed to very specific and harsh conditions such as offshore environments. Adequate and detailed record of the procedures implemented should be performed in order to assess the performance and durability of the protective system. This type of data may provide essential information on possible problems regarding the coating application or performance, for instance premature coating failure. Furthermore, these types of statistics may be an important tool for future selection/development of protective coating systems.

EN ISO 12944-7:1998 [147] addresses the supervision of paint procedures and states that all the stages of painting should be verified and supervised by qualified technicians with adequate technical knowledge. The level of supervision depends on the type of coating and importance of the structure, local conditions, difficulty of coating application and desired durability. The quality of the paint is generally checked before and during coating procedures. These assessments are generally performed in the lab and in the field. Lab tests are often time consuming. Nevertheless, simple tests can be carried out in the field such as checking the colour, density and viscosity of samples randomly. The wet film thickness can be periodically checked during application. All equipment and instruments used should also be checked, calibrated and maintained at systematic periods. The coatings should be checked for agreement with specifications. Quick tests may be performed, for instance, by visual assessment to check the colour, defects and uniformity of the paint. The dry film thickness should be assessed according to EN ISO 2808:2007 [173], the adhesion should be determined according to EN ISO 2409:2007 or EN ISO 4624:2002 [174] and the porosity measured by flow or high-voltage detectors.

The nominal dry film thickness for different types of paints is discussed in EN ISO 12944-5:2007 [71] and is recommended that the dry film thickness does not exceed more than three times the nominal dry film thickness [71,147] or the limit provided by the manufacturer. On both rough and smooth galvanized surfaces, thickness of the dry film should be checked in accordance with ISO 19840:2004 [175] and EN ISO 2808:2007 [173]. An individual dry film thickness less than 80% of the nominal dry film thickness is acceptable if the average is equal to or greater than the nominal dry film thickness.

It should be mentioned that reference areas must be stablished on the structure [147] to assess the coating any time after application. The reference areas should be localized in places where the corrosive stresses are typical considering the type of structure. The size and the number of reference areas for the assessment of the coating is dependent on the size of the structure and should be determined and agreed between the parties involved [147].

3.7. Health Safety and Environmental Regulations

All requirements concerning the health, safety and environmental protection should be considered. The personnel involved in a project are responsible for safeguarding their own health and safety in addition to the health and safety of all the other workers while performing work procedures. Furthermore, all working procedures should be performed in accordance with the requirements of each country where work is being performed.

Paints and coatings must be handled with caution. All health and safety recommendations provided by the manufacturer should be followed during the working procedures to avoid any health risks. Epoxies may cause dermatitis after extended contact and hardeners from PU may affect the respiratory system. Additionally, most of the solvents are flammable and harmful to human skin. Mixing the paints and coatings requires protection due to the risk of breathing paint particles and to solvent inhalation.

Table 11 shows the Volatile Organic Compounds (VOCs) content of some generic types of paints. According to EN ISO 12944-5:2007 [71], paint products with low VOCs content are known as high-solids solvent-borne products, solvent free-products, or water-borne products. High-solids solvent-borne and solvent free products (100% solids without volatile content) are generally suitable for submerged conditions. The water-borne products may be employed in nearly all atmospheric corrosivity categories.

Table 11. Typical Volatile Organic Compound (VOC) range for generic type of paints.

Typical VOC Range/gL^{-1}	Generic Type of Paints	Alternatives
>500	Poly(vinylchloride)copolymer	Water-borne
	Acrylic	
	Chlorinated rubber	No
350–650	Zinc silicate	Water-borne and high-solids
330–500	Alkyd	
0–700	Epoxy	Water-borne, high-solids and solvent-free
0–500	Polyurethane (aromatic)	
	Polyurethane (aliphatic)	

Risk and safety assessments should be performed prior to any activities involving the use of the paint products. All personnel should be aware of the safety cautions and procedures of the actions to be taken in case of accident. The working areas should be well ventilated and all the personnel involved should be protected with suitable personal protection equipment. Data sheets on safety requirements of the product must be provided. These must give full details of threshold level values, lower explosive limits, necessary precautions for any particular form of application and any other hazards applicable. Safety and risk analysis should be carried out and generally, the measures that should be adopted to reduce the risks related with the various paint systems are:

- Protection of the body, including eyes, skin, ears and respiratory system;
- Protection against harmful effects of fumes, dust, vapours and noise as well as fire hazards;
- Protection of water and soil during coating application works;
- Low VOCs content products should be selected;
- Appropriate ventilation should be provided particularly in confined spaces;
- Recycling of materials and disposal of waste must be carried out.

4. Coating Performance and Assessment Techniques

The assessment of steel structures requires the use of a classification system able to identify and quantify any defect that compromises the safety and/or function of part or the whole structure. Several methodologies can be found in the literature. The primary causes for failure of steel structures can typically be attributed to one of the following: Poor design assumptions, errors during fabrication or construction, unexpected actions during service life, poor quality of materials, or a combination of these. Various deterioration processes can act on a steel structure simultaneously. The two most common of these deterioration processes are corrosion and fatigue.

When classifying defects in a structure, the first level of classification involves identifying the defect as one of the following: contamination, deformation, deterioration, discontinuity, displacement or loss of material. The second level of classification identifies the structural components where the defects tend to occur. Lastly, the third level specifies the subtype of defect. Table 12 shows the classification of defects in steel structures and some pictorial representations.

Table 12. Classification of defects in steel structures and some examples.

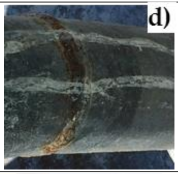
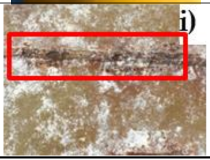
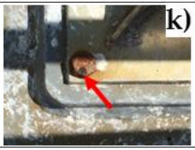
Types of Defects (1st Level)	Structural Components (2nd Level)	Subtype of Defects (3rd Level)	Examples
Contamination	Steel	Chemical (a) Salts on steel surface caused by environmental exposure	
		Biological (b) Microorganism on the surface of structural elements of the OWS	
Deformation	Basic component	Deflection, Distortion, Torsion (c) Distortion of a metallic element	
	Riveted/bolted connector		N/A
	Welding	Deflection, Torsion (d) Welding deflection of a metallic element	
Deterioration	Basic component	Uniform (e) Uniform deterioration on a metallic element on an OWS	
		Localized (f) Localized deterioration around bolt holes on a metallic element	
	Bolted/riveted connector	Uniform (g) Uniform deterioration in a bolted connector	
Deterioration	Coating system	Rusting (h) Rusting in the coating system	
	Welding	Uniform (i) Uniform deterioration in a welding	

Table 12. *Cont.*

Types of Defects (1st Level)	Structural Components (2nd Level)	Subtype of Defects (3rd Level)	Examples
Discontinuity	Basic component	Crack (j) Crack of a metallic element.	
	Bolted/riveted connector	Crack or fracture (k) Crack of a bolted connector	
	Coating system	Delamination/Flaking (l) Delamination and flaking of the coating system	
	Weldings		
Displacement	Steel	(m) Displacement defect	
Loss of material	Steel	(n) Loss of material of a metallic element	

Note: All images are courtesy of PPI, Principle Power Inc. (Emeryville, CA, USA).

The decision-making process for maintenance or repair of OWS must be supported by careful analysis during assessment of the global condition of the structure. Damage typically occurs in OWS due to fatigue, corrosion and degradation of the coating system and each condition has its own techniques of inspection. Correct assessment of a structure condition relies on suitable combination of the different methods available. Inspections are crucial to assess and characterize the damage and ultimately identify the underlying causes and deterioration mechanisms. The adequacy of each testing technique may be complex and typically requires expert advice. Inspection adequacy is influenced by several factors: availability of technical specifications, knowledge of limitations and feasibility of the technique, and a full understanding of the material properties of the specimens to be assessed.

Several non-destructive methods (NDM) are available to assess the structure without adversely affecting its performance. NDM's aid in identifying or quantifying the defects that may affect the service life of the structure. Destructive methods (DM) may also be used to complement or further characterize the materials properties (mechanical, chemical, corrosion resistance and fatigue). DM provide reliable and quantitative data while NDM allow performing fast tests that can be repeated. Due to the destructive nature of DM's, they are typically only employed upon decommission of an OWS. The complexity related to damage on metallic structures in offshore environments generally requires the combination of different techniques and, thus, expert consultation is needed in more intricate cases.

4.1. Non-Destructive Methods (NDM)

The most common non-destructive methods (NDM) applied to old and new structures are visual inspection, Foucault currents, magnetic particle inspection (MPI), liquid penetrant testing (LPT), radiography and gammagraphy, acoustic emission testing (AET), ultrasonic methods (UM), dynamic vibration method and magnetic flux and flux leakage. For new structures, the main applications of these NDM are for quality control or to check the quality of materials/construction. NDM are generally used to assess the structural integrity or adequacy of the structures prior to the use of destructive tests [176]. The following section will be focused only on the NDMs that are suitable for coatings assessment, namely visual inspection, Foucault current inspection, and UM.

4.1.1. Visual Inspection

Visual inspections are widely used as a pre-condition to other detailed inspections. Visual inspections can be performed on all types of metallic structures and defects. Visual inspection allows for the immediate detection of degradation such as corrosion (presence of corrosion products), broken cables, cracks, deformation, among others pathologies. Observation is performed by the inspector or via an endoscope. The test procedure and the interpretation of results should be performed according to EN 13018:2001 [177].

The advantages of this method are the easiness and speed that can be conducted allowing a frequent update of the structural health condition. Nevertheless, the inspector should bear in mind that this method is based on the interpretation of defects and is only a qualitative assessment of the visible and accessible parts of the structure. Additionally, it is important to note that cracks or defects occurring below the surface of the steel may not be detectable by visual inspection. The coating system can be used to aid in the process of crack detection in the steel. If cracks are visible in the paint system, there exists a higher likelihood of cracks in the steel below and thus paint removal and visual inspection of the underlying steel should be performed. If the paint is not properly adhered to the underlying steel, this method will not be possible.

Visual inspections may be affected by several factors, such as:

- Number of inspections performed annually;
- Structure accessibility and complexity;
- Comfort to access heights;
- Visual acuity and colour vision;
- Luminosity during inspection;
- Time to complete the inspection;
- Inspector knowledge and experience level;
- The overall precision with which the inspectors carried out the inspection.

The results of the visual assessment of the structure should be used to fill and update the structural health condition document. The numerical treatment of pictures using suitable software can help in the quantification of the defects. Upon the conclusion of the visual inspection, all of the data is gathered and analysed to determine if further inspection with a more powerful NDM is necessary.

4.1.2. Foucault Current Inspection

Foucault current inspection, also called Eddy currents, is a method based on the principle of magnetic induction used to inspect metallic parts and detect surface and near surface defects [178–180]. This technique allows measurements of non-conductive coating thickness, detection of defects and changes in the properties of the coating systems [178], and detection of cracks in rivet holes. The Foucault currents are loops of electrical current induced within conductors by a changing magnetic field in the conductor. An electromagnetic field is generated with the aid of a coil, where an alternating current is flowing; this magnetic field is used above the specimen to assess. The properties of the materials or the presence of discontinuities and defects in the test samples affect the magnitude and phase of the induced current. The number, size, and density of defects such as cracks will impact the magnitude and phase of the induced current further. Changes in the electrical conductivity or magnetic permeability of the coating/material or the presence of any flaw will cause a change in the

Foucault currents flow and a change in the phase and amplitude of the measured current will occur. The first step when using this method is select and setup the instrument, probe and frequency (which is related to the depth of penetration). A preliminary calibration on a reference area of steel is required. After calibration, a scan of the surface is carried out and the same probe-to-surface orientation must be maintained during the measurements. Local changes in impedance will appear when the probe moves over a discontinuity. If, for any reason, the coating systems experience a property change (such as permeability, hardness, brittleness, or reduction of intercoat adhesion) then the barrier properties will degrade and this can be detected by Foucault current inspection through local impedance changes. The main advantages of this method are the high sensitivity to minor defects/discontinuities; and no mechanical contact occurs with the inspected surface. However, Foucault current inspection is a technique that only allows qualitative defect detection because it has limited depth of penetration in the materials. Also, it can be difficult for the inspector to distinguish between the signal and the noise when analysing the results. Therefore, a prior knowledge of a probable defect type and its position is necessary before using the Foucaul current inspection method [178].

4.1.3. Ultrasonic Methods (UM)

UM are widely employed to detect fatigue or weld cracks, cavities, porosities, and discontinuities both on the surface and internally [181,182]. These methods also allow thickness measurement of the metal, corrosion products and coatings. In UM, a mechanical wave is emitted by a transducer and propagates within the structure. Depending on the source, a compression wave or a shear wave can be generated. This signal is reflected by the defects or ends of the structure and produces echoes. The echoes are recorded by the same emitting device or another transducer called a receiver on a digital acquisition system. The time of propagation from through the metallic structure can be used to estimate its thickness [181,183].

Crack detection by UM is performed generally at a frequency range between 0.1–25 MHz. Two modes are used, transmission and echo-pulse. In echo-pulse mode, the transducer sends ultrasonic pulses into the metallic substrate that travel through the material and are reflected back to a specific receiver near the emitting one (or to the transducer that also acts as a receiver). The reflected wave comes from a reflective surface such as a defect or the back wall. The results are displayed in a graphical representation of amplitude versus distance. The presence of a defect is characterized by an extra signal between the initial and back wall signals. In transmission mode, an emitter sends waves through the substrate and a receiver, placed at the opposite side, detects the ultrasound intensity that has been reached. Flaws or discontinuities between the emitter and receiver reduce the intensity of the waves and, thus, reveal its presence. The analysis of the magnitude of the reception peak allows detection of the flaws; however, the length cannot be established. A couplant (grease) is used to increase the efficiency of the inspection by reducing the signal loss due to the change in acoustic impedance between the surfaces of transducer and the metallic substrate.

Prior to thickness measurements, the metallic parts are cleaned and the areas to be measured are defined and minimized to the extent necessary. Considering the operational constraints and implementation costs, the measurements require a representative sampling of the entire structure.

UM is easy to use, sensitive, and provides accurate thickness measurements. Also, UM detects discontinuity position and orientation with high precision. The main disadvantages of UM are linked to the need of highly qualified personnel (knowledge on UM and metallic structure inspection). Additionally, the types of defects and their geometry may compromise the results. Finally, a meticulous surface preparation to ensure a coupling between transducer and structure should be kept in mind since it may influence the scatter of measurements.

There are some applications currently under development such as the design and construction of a prototype system using Ultrasonic Guided Wave technology to monitor the integrity of offshore structures such as wind turbine towers [184]. Also, NDM have been developed for the examination of critical welds and lengths of sub-sea pipelines [185]. The NDM systems and sensors developed for sub-sea remote operating vehicle (ROV) deployed applications include: phased array automated ultrasonic testing for the volumetric examination and alternating current field measurement for the surface and near surface examination of critical sub-sea jacket welds on structural tubulars, support legs and node sections; and long range ultrasonic testing using guided ultrasonic waves for the examination of sub-sea flow lines, oil & gas import and export lines and risers for corrosion and other volumetric defects [185].

4.2. Destructive Methods (DM)

Destructive techniques can be classified as accelerated electrochemical (corrosion tests), metallographic, or mechanical (fatigue and tensile tests). Several methods for electrochemical characterization are available. Nevertheless, only polarization resistance, dynamic potential curve and electrochemical impedance spectroscopy will be discussed in this section. The choice of these three techniques is related to the amount of information that can be extracted and the ease with which they can be implemented in the lab. The corrosion behaviour of the steel substrate is assessed in a specific medium, which is very often sea water or simulated sea water with NaCl in accelerated environment by increasing the temperature or using more aggressive environments than the ones found in service [68]. Metallographic tests and studies are conducted to assess the relationship among the microstructure of the analysed specimens, the degradation mechanism, and its evolution. Different chemical analyses can also be performed. These methods are used for the determination of the chemical composition of steels and corrosion products. The identification of the steel type and grade can be established by comparing the results with the product specification. The corrosion products and the type of oxides formed on the surface of the specimens can be characterized by comparing the results with the reference specimens. Recently, a review focused on the localized electrochemical characterization of organic coatings has been published [186]. The authors discussed several electrochemical techniques applied to organic coatings, such as scanning electrochemical microscopy (SECM), scanning vibrating electrode technique (SVET), local electrochemical impedance spectroscopy (LEIS), scanning kelvin probe technique (SKP), scanning reference electrode technique (SRET), and scanning ion-selective electrode technique (SIET). The authors concluded that the reviewed techniques can provide resolution at a microscopic and sub microscopic level allowing the understanding of fundamental processes of corrosion, and characterization of defects in alloys and underneath organic-based coatings. SKP measures the corrosion potential of a coated/metal surface and is of particular interest for defect characterization in organic-based coatings. SKP has been used for delamination characterization of organic-based coatings and to locate defects in organic polymer films [186,187].

4.2.1. Corrosion Tests

The corrosion process is typically electrochemical in nature. For that reason, electrochemical characterization techniques are considered the most appropriate to understand the corrosion behaviour of structures and the protective performance of the coatings. Corrosion tests provide data to assess and/or select alternative materials in different environments. Corrosion monitoring allows for observation of the behaviour of the system chosen for corrosion control/mitigation by providing warnings when damage occurs. Electrochemical tests are more important in assessing the corrosion resistance of materials and coatings and the effect of the changes in the environment than as a failure analysis tool [68]. Furthermore, it is beyond of the scope of this manuscript to detail all existing corrosion tests.

Prior to the corrosion test itself, it is necessary to prepare the specimen to be tested. The metallic substrate is degreased with a solvent and rinsed with distilled water while the surface area to be tested is determined. Generally, the electrochemical cell used is a three-electrode system composed of the working electrode (substrate to be studied coated), counter electrode (platinum or other noble material) and reference electrode (generally saturated calomel electrode). The electrodes are placed in a glass container with the solution to which the substrate is exposed or a simulative solution of the environment (corrosive solution). A salt bridge with a Luggin probe or other set-up is used to separate the solution from the reference electrode. The specimen is immersed in the corrosive solution and held with a specimen holder. The corrosion potential (E_{corr}) is recorded for a few hours (typically one to five hours) until stabilization is reached. Once the E_{corr} is stable, the different electrochemical methods can be used to characterize and understand the corrosion behaviour of the specimens.

4.2.1.1. Polarization Resistance (R_{p})

The corrosion rate can be obtained from the polarization resistance measurements. This method is based on the observation of the linearity of the polarization curve near the E_{corr}. The application of a small increase of potential, ΔE, generally +10 mV, around the corrosion potential (E_{corr}) is translated in a current variation, ΔI in a certain period of time. The polarization resistance, R_{p}, is defined as [188]:

$$R_{\text{p}} = \left(\frac{\partial \Delta E}{\partial i}\right) \Delta E \to 0 \tag{1}$$

The current corrosion density, i_{corr}, can be obtained from the R_{p} values using the following equation:

$$i_{\text{corr}} = \frac{B}{R_{\text{p}}} \tag{2}$$

where B represents a constant dependent on the Tafel slopes of anodic and cathodic processes, respectively β_{a} and β_{c}:

$$B = \frac{\beta_{\text{a}} \times \beta_{\text{c}}}{2.303\ (\beta_{\text{a}} + \beta_{\text{c}})} \tag{3}$$

B is between 13–52 mV for a great range of metal/electrolyte systems [189]. The corrosion current density may be converted in corrosion rate, V_{corr}, in mm/year using the Faraday law. The corrosion rate determinations can simplify the estimation of the deterioration progress of a structure and predict the residual lifetime [118] which is very useful for structures in locations with difficult access such as OWSs.

Furthermore, the coating porosity (expressed in percentage) can also be determined from the following equation [190,191]:

$$\text{Porosity } (\%) = \frac{R_{\text{ps}}}{R_{\text{p}}} \times 10^{-\frac{\Delta E_{\text{corr}}}{\beta_{\text{a}}}} \times 100 \tag{4}$$

where R_{p} is the polarization resistance of the coating, R_{ps} is the polarization resistance of the bare substrate, β_{a} is the anodic Tafel slope of the bare substrate, and ΔE_{corr} is the difference between the corrosion potential of the coated and the bare substrate. The porosity of a coating is an important property since it is related to the ability to absorb and release molecules or ions. The ability of an organic-based coating to absorb moisture or allow it to diffuse through the metallic substrate may compromise the coating performance. For example, blistering of an organic-based coating may occur due to the presence of water under the coating (water uptake) [85].

4.2.1.2. Potentiodynamic Polarization Method (PPM)

This method is used to characterize the electrochemical behaviour of a metallic substrate in a selected medium. Both cathodic and anodic zones are studied. Potentiodynamic polarization is an electrochemical technique where potential of an electrode, with respect to a reference electrode, is scanned continuously and the corresponding current density is recorded. The potential of an electrode is changed at a selected rate by application of a current through the electrolyte [68,188]. The potential scan starts from the E_{corr} in the anodic direction. This starting point can also be in the cathodic range. The scan rate must be chosen considering a fast, medium or slow scanning for electrochemical reactions to achieve equilibrium. The corrosion rate is assessed through the Tafel extrapolation method. This technique allows to measure the protection efficiency (*PE*%) of a coating [190,192]. The PE of the coating can be determined using the equation:

$$PE\ (\%) = \left(\frac{i_{\text{corr}} - i^{*}_{\text{corr}}}{i_{\text{corr}}}\right) \times 100 \tag{5}$$

where, i_{corr} and i^{*}_{corr} are the corrosion current densities obtained for the metallic substrates without and with the coating respectively. This curve allows the tester to determine the uniform corrosion rate from Tafel slopes and the potential ranges where corrosion is active, as well as the characteristics of a localized corrosion such as pitting (E_{pitting}). Each material-medium combination has its own features. The main advantage is the determination of corrosion properties and by using some assumptions is possible to assess the remaining lifetime of the metallic substrate in a certain environment [68,188].

4.2.1.3. Electrochemical Impedance Spectroscopy Method (EIS)

In the last decades, EIS has been widely used for coatings characterization [119,120,193–202]. EIS is a transient technique where a sinusoidal signal (potential) is applied with low amplitude, to not disturb the equilibrium conditions of the system. The response, as a function of frequency, is measured. EIS allows the characterization of interfacial and bulk properties of a wide variety of materials. Many electrical parameters of a system may be obtained from a single EIS experiment, such as resistance, capacitance and dielectric constant [197,203]. The results obtained by the EIS measurement, in the set range of the frequency values, are represented in the Nyquist and Bode plots. Figure 5 shows typical Nyquist plots obtained for coated HDGS and the respective EEC.

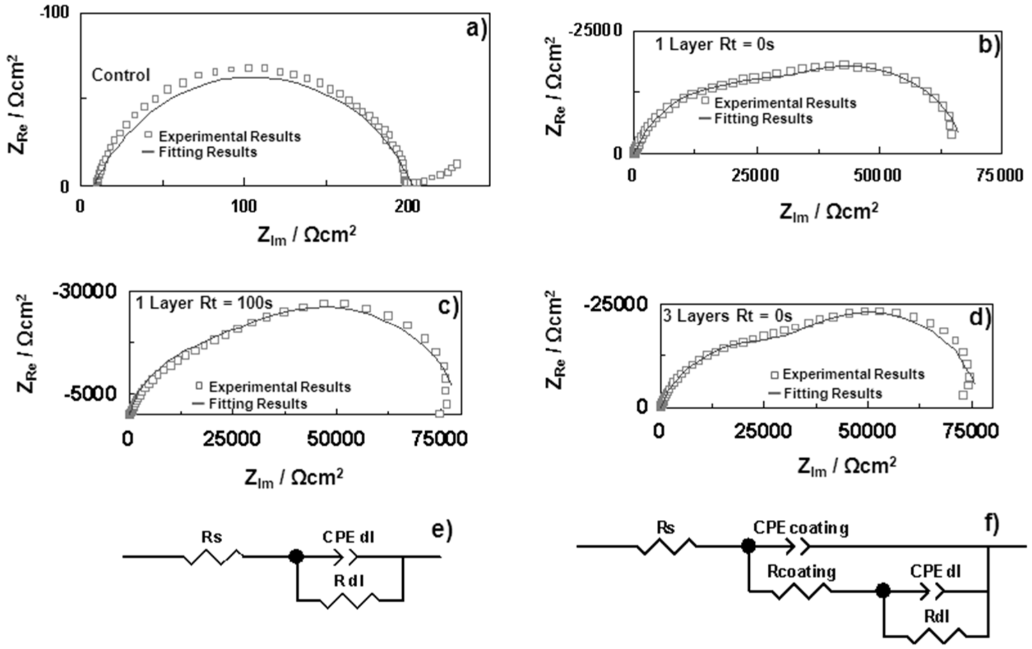


Figure 5. Nyquist plots for: (**a**) Control and coated HDGS samples with one layer deposited by dip coating; (**b**) without residence time (R_t = 0 s) and (**c**) with residence time (R_t = 100 s); (**d**) HDGS samples coated by three consecutive dip steps and R_t = 0 s in the instants of exposure to highly alkaline solution. EECs used for numerical fitting of the Nyquist plots for: (**e**) Control and (**f**) coated HDGS samples. Reprinted with permission from *Coatings* MDPI [204].

The main difficulty in obtaining reliable and consistent results with this technique relies on the choice of suitable and correct electrical equivalent circuit (EEC) to model the EIS data. Depending on the complexity of the EEC chosen, several parameters are involved in obtaining the best fitting of the EIS results. The resistance of the coating is one of the parameters to be modelled. Therefore, if an inappropriate EEC is chosen, or some of the parameters are incorrect, the values of the coating resistance are not accurate and may lead to incorrect conclusions EEC [197,203].

4.2.2. Metallographic Tests

Besides corrosion tests (electrochemical techniques), methods to assess the morphology and microstructural parameters such as thickness, defect rate and morphology of the surface are of extreme importance. These structural parameters can be achieved by macroscopic techniques (binocular magnifying systems) or microscopic using light microscope or scanning electron microscope (SEM). Optical light microscopy allows for the examination of a small region or area of unprepared or polished normally etched surface at a magnification of 25 to 1000× [68]. The accuracy of the resolution limit is about 0.5 µm. Current examination is of the sample cut from the bulk. This technique also provides information about the subsurface damage (on cross sections) including damage initiation, secondary damage/cracking and propagation. It is also possible to establish a relationship between the structure and damage/properties [68]. The corrosion layer and coating thicknesses are assessed and measured by cross-sectional observation. For corrosion products, analysis of the surface of the samples is observed without any preparation (Figure 6). SEM allows examination of unprepared or prepared samples (polished and etched) if the surfaces are electrically conductive. If not, this may be achieved by coating the samples with gold by sputtering technique. The precision with SEM is under 100 nm. In the last few decades, several coatings have been developed, particularly hybrid sol-gel coatings and self-healing coatings among others. Figure 7 is an example, of the type of information that can be achieved from a cross-section observation. Figure 7 shows a cross-section of HDGS coated with an organic–inorganic hybrid (OIH) coating obtained by sol-gel method and deposited by dip-coating method [89,117,118]. The image shows the thickness values obtained for HDGS in different places (21 and 23 µm) and one thickness value for the OIH coating (15 µm). Metallographic tests have several advantages. They are precise techniques for the analysis of coating defects and thickness measurements (quantitative analysis). Photographic recording on-site is also possible [68]. The main disadvantages include the need of highly skilled and trained technicians and the destructive aspect of specimen preparation and sampling. Furthermore, a considerable number of test specimens are required. In case of SEM, the data interpretation is moderate to difficult and may require experience as well as specialized equipment.

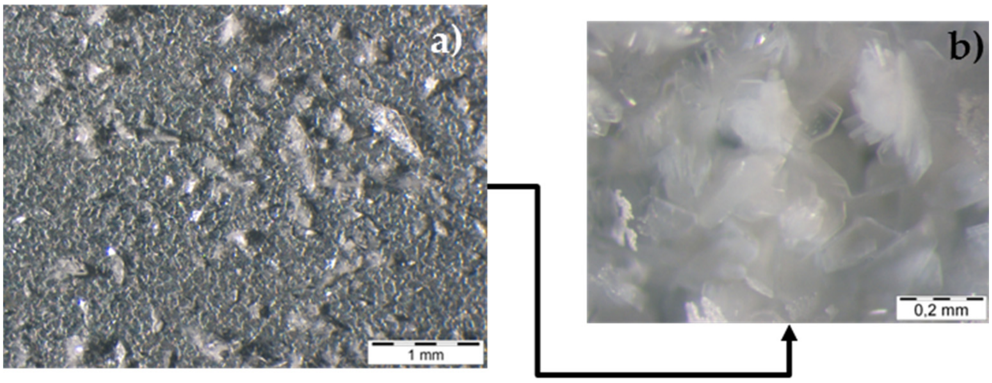


Figure 6. Stereoscopic observation of the corrosion products formed on HDGS during immersion in highly alkaline solution. (**a**) Generic view and (**b**) detail of the morphology of the calcium hydroxyzincate crystals formed.

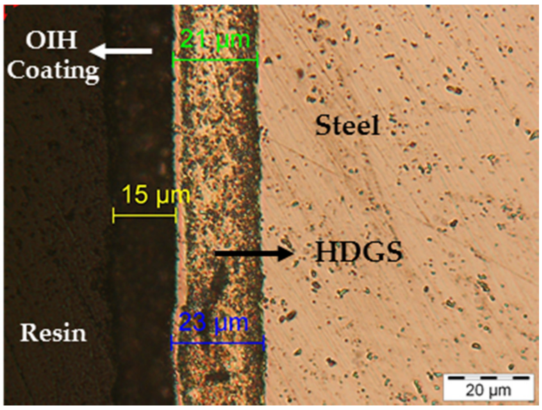


Figure 7. Cross-sectional observation of HDGS coated with an organic-inorganic hybrid (OIH) coating obtained by sol-gel method.

4.2.3. Chemical Analysis

Different analytical techniques and tools have been developed to provide information concerning the chemical composition of surface constituents, however, only a brief reference to the most representative techniques will be given. Several techniques are available for bulk chemical analysis that can be accessible with Optical Emission Spectroscopy (OES) and Glow Discharge Optical Spectrometry (GD-OES) (Figure 8). Near surface chemical analyses which allow elements detection in extremely thin surface layers, can be achieved by Electron Diffraction Spectroscopy (EDS); wavelength diffraction spectroscopy (WDS); X-ray photoelectron spectroscopy (XPS); secondary ion mass spectroscopy (SIMS); low-energy ion-scattering spectroscopy (LEISS). In the last two decades, several localized electrochemical techniques have been developed. Besides the electrochemical information provided by SECM, this technique can also provide topographic and chemical information about the sample surface in solution [186]. One of the main advantages of SECM is its high spatial resolution capability to detect chemical species in localized corrosion processes [186]. Information about molecular composition can be given by Raman spectroscopy or X-ray diffraction. These analyses can be conducted on plane surfaces with corrosion products, organic-based coatings (paints), metallic coatings, oxides, etc.

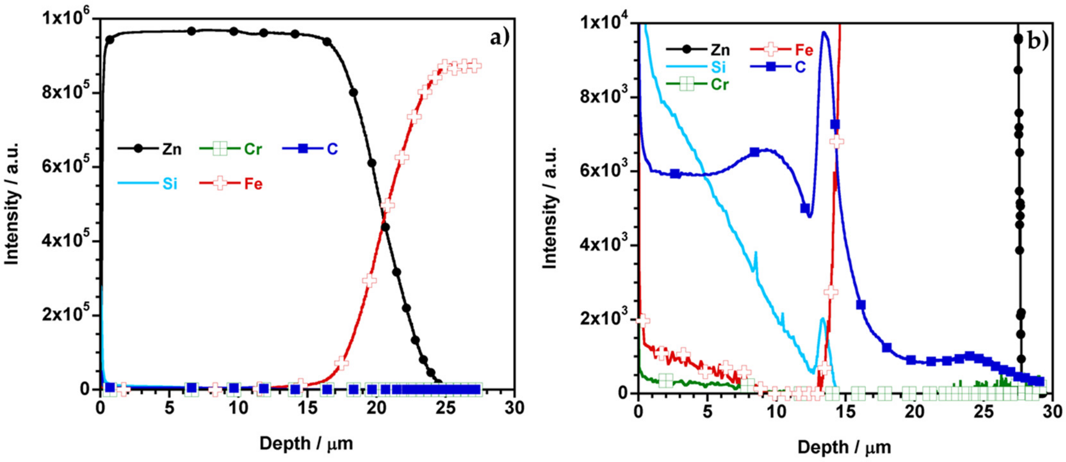


Figure 8. GD-OES depth profiles for Zn, Si, Cr, Fe and C for (**a**) HDGS coated with 1 layer of OIH synthesized by sol-gel method. Detailed view is shown in (**b**).

Can also be performed on cross-sections or on the surface of the fracture. OES and GD-OES techniques have some important advantages. All elements can be detected; the measurements are fast and are techniques with high sensibility (>20 ppm mass for OES and > 10 ppm for GD-OES). The main limitations concern the sample dimensions and the fact that are destructive methods. EDS technique allows qualitative and quantitative chemical analysis of the specimen composition and when used with a scanning electron microscope the EDS system can analyse element distributions within an area of interest (Figure 9). The sample dimensions and sensibility (>0.1% mass) are limited. As a representative example, Figure 9a shows a SEM image of a sample of HDGS uncoated (1) and coated (2) with a hybrid sol-gel coating [118,199,200]. The EDS analysis is also shown (Figure 9b,c) and is clearly observed the presence of Carbon (C), Silicium (Si) and Oxygen (O) in the coated area which cannot be found on the surface of uncoated substrate and only zinc was detected.

The chosen method must analyse the required elements according to their assumed depth. Surface methods are EDS and WDS. GD-OES and OES are volumetric methods. The choice of a technique must be adapted for the sample's physical characteristics such as size, geometry, limitations in sample preparation or its preservation. Table 13 condenses the techniques that were discussed in the previous sections. The information extracted, advantages and disadvantages, and limitations are summarized. Table 14 shows the adequacy of each NDM and DM according to the defect type.

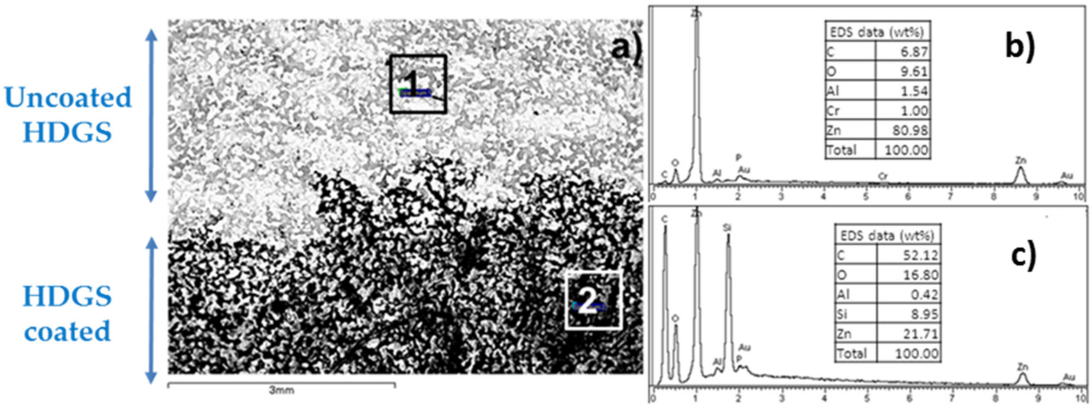


Figure 9. (**a**) SEM image of HDGS surface (backscattered mode) showing (1) uncoated and (2) coated areas with the localization of Electron Diffraction Spectroscopy (EDS) analysis (**b**) and (**c**) (including semi-quantitative analysis as inset).

4.3. Fatigue Assessment

Prior to the identification of fatigue cracking, fatigue assessment procedures play an important role in the selection of remedial measures. Critical areas of the structure need to be identified when designing the structure for fatigue. The criticality of the area in combination with its ability to be inspected and repaired will help determine the safety factor used for fatigue design. Details of the structure such as welded and riveted/bolted connections need to be identified and monitored closely to assess any possible damage. The cause of any fatigue crack must also be established in order to adopt suitable measures which include repairing and strengthening. Other measures may also be considered such as intensification of monitoring of the crack grow or, in worst case scenario, earlier decommission of the OWS. Eurocode 3, Part 1-9:2005 [205] identifies the different types of connections in steel structures where fatigue failure is likely to occur. The selection of appropriate remedial measures requires an assessment by a qualified structural engineer. The remedial measure depends on the location, size, and cause of fatigue damage. Eurocode 3, Part 1-9:2005 [205] provides two methods for fatigue assessment:

Table 13. Summary of techniques discussed in the previous sections.

Technique	Information Extracted	Advantages	Disadvantages/Limitations
Visual inspection	General extent of damage/failure	May be conducted on-site; the whole structure may be examined; It is not required specialized equipment and the operator can make a photographic recording	Low resolution about the initiation and spreading of the damage as well as the mechanisms involved and source of the problem
Foucault Current	Detection of cracks or defects and thickness of non-conductive coatings	Quick and simple, suitable for on-site/remote use. Standard for inspections exist and all electrical and conducting materials	Only near to surface defects or cracks are detected. Moderate difficulty in the data interpretation; the resolution is sensitive to the operator
UM	Thickness of material up to 250 mm	Sensitive; portable equipment available and applicable to a wide range of materials	Cracks/bonds normal to wave may give unreliable results
R_p	Corrosion rate	Assess the remaining lifetime of the structure	Representative sampling and artificial electrolyte that simulates the natural exposure
PPM	Corrosion rate, potential ranges where corrosion is active and detect localized corrosion		
EIS	Resistance and capacitance	–	–
Optical (light) Microscopy	Surface condition and microstructural features. Cross-section observation allows observation of the subsurface damage. Thickness measurements	Precise technique coating defects analysis and thickness measurements (quantitative analysis)	Highly skilled and trained technicians, destructive aspect of specimen preparation and sampling. A considerable number of test specimens is required
SEM	Microstructural features and relationship between damage and structure, distribution of porosity, cracks and voids	High resolution (under 100 nm). Minor specimen preparation. Elemental chemical analysis is possible if coupled to an EDS.	A highly skilled and trained technician, data interpretation is moderate to difficult and may require experience. Specialized equipment
EDS	Qualitative and quantitative analysis of chemical elements	Carried out together with SEM	Specialized equipment in conjunction with SEM. Near-surface analysis. Highly skilled and trained technicians. Elements analysed with $Z > 5$ or > 11. Sample dimension is limited
GD-OES	Qualitative and quantitative analysis of all chemical elements	High sensibility (>10 ppm), rapid analysis, all elements can be detected	Sample dimension is limited
Raman spectroscopy	Molecular composition	Molecular information	Elements analysed with $Z > 5$ or > 11. Sample dimension is limited

Table 14. Adequacy of each non-destructive methods (NDM) and destructive methods (DM) according to the defects (deterioration and discontinuity).

Type of Deterioration	**Basic Component**		**Bolted/Riveted Connector**		**Welded Connector**		**Coating System**	
	Uniform	**Localized**	**Uniform**	**Localized**	**Uniform**	**Localized**	**Uniform**	**Localized**
NDM	Visual inspection, UM	Visual inspection, radio/gammagraphy, UM; Foucault Current	Visual inspection, UM	Visual inspection; UM; Foucault Current	Visual inspection, UM	Visual inspection; UM; Foucault Current	Visual inspection, UM; radio /gammagraphy (metallic coatings)	
DM	Tensile testing; Fracture testing; Hardness; Chemical analysis, Metallography, Electrochemical methods				Chemical analysis, Pull off; Metallography			
Type of Discontinuity	**Crack**	**Fracture**	**Crack**	**Fracture**	**Crack**	**Fracture**	**Flaking**	**Delamination**
NDM	Visual inspection; UM; radio/gammagraphy; Foucault currents				Visual inspection, Foucault currents			
DM	Tensile testing; Fracture testing; Hardness; Chemical analysis, Fatigue testing; Metallography and Fractography in case of fracture						Pull off; Metallography	

- Damage tolerant method—this method is based on the proper performance of a structure during its service life with the implementation of adequate plans of inspection and maintenance. The structure may be considered reliable with the following conditions.
- Selection of materials, details and design, which, in case of crack initiation would result in a low rate of crack propagation and in a long critical crack length.
- Implementation of multiple load paths and details capable of arresting cracks that can be easily inspected during the planed inspections.
- Safe life method—this method is based on the proper performance of the structure without the need of regular inspections by providing an acceptable level of reliability. The reliability of the structure depends on selecting details and stress levels, which would result in enough fatigue life to achieve values equal to those for ultimate limit state verifications at the end of the design life.

The Recommended Practice DNV-RP-C203 [206] reports the recommendations that should be adopted in the design of OWS.

4.3.1. Methods to Improve Fatigue Resistance

The most common methods, generally employed, during the fabrication of an OWS to improve fatigue performance are grinding and peening.

4.3.1.1. Grinding Methods

Grinding methods are commonly used as fatigue improvement technique in welded structures by modifying the weld profile. These are also employed to repair small fatigue cracks, nicks and gouges, to smooth welds, edges, etc., prior to the general finishing of surface preparation for the application of coating systems. Concerning the removal of fatigue cracks, grinding is suitable when the latter are caused by welds defects and web gaps. However, grinding can be also used for defect causes such as cold cracks, lack of fusion, vibration, restraint or geometrical variations. Grinding methods allow the removal of small cracks up to 25.4 mm long and 12.7 mm deep and are suitable to remove nicks and gouges up to 5 mm deep, ensuring that the cross-sectional area remains at least 98% of the original after removal of the notch [207,208]. However, when dealing with plates thinner than 8 mm, grinding is not suitable [207]. The final surfaces should be clean, smooth and without any signs of slag or undercut. The depth of removed material should also be inspected with a suitable gauge. Depth scratches parallel to the length of the weld should not be accepted by the inspector and a smooth transition between the weld and the metallic base is expected [80,83,209].

A visual inspection to ensure the correct execution of grinding should be performed. The inspection of the weld should be carried out using NDT methods such as MPI according to EN ISO 17635:2003 [210] and BS EN ISO 23278:2009 [211] or LPT according to BS EN 571-1:1997 [212] and BS EN ISO 23277:2009 [213]. This will ensure a weld toe free from any traces of undercut and that embedded flaws are not exposed. Two types of grinding are common, rotary grinding and disc grinding. Rotary burr grinding is more expensive and requires more renewal than disc grinding. The rate of burr grinding is less than that of disc grinding and makes it a slower tool [207]. Furthermore, it has been reported that the improvement in fatigue strength from rotary burr grinding at 2×10^6 cycles ranges from 50% to 200% depending on the type of joint and from 20% to 50% for disc grinding [214]. There are no European standards to regulate the repair of metallic structures using grinding methods. Nevertheless, the main concerns are linked to the excessive removal of material that may weaken the strength of the repaired element. Concerning the weld profile improvement the acceptable grinding depth ranges between 0.5 mm and 2 mm or 5% of the plate thickness [214]. In corrosive environments, such as offshore, an adequate corrosion protection system should be provided; otherwise, the corrosion roughness on the smooth surfaces can reduce the benefits of grinding on fatigue [214].

4.3.1.2. Peening Methods

Peening is a cold working process that plastically deforms the material by impact with a tool or metallic particles. In this process a beneficial residual compressive stress is produced on the surface by work hardening. The compressive stresses aim to replace the residual tensile stresses of as-welded elements that are detrimental due to crack susceptibility and therefore improving the fatigue strength. The deformation induced by peening also improves the weld toe geometry and smoothness the transition between the weld and the metallic base, which reduces the local stress concentration. Peening methods offer good results for fatigue causes such as cold cracks, vibration, restraint, web gaps and lack of fusion. These methods are also very effective for repairing shallow surface cracks which, occur in the fillet weld toe and for improvement of fatigue resistance of the weld [81].

Peening methods can also be used in the intermediate layers of weld and are considered to be favourable in the prevention of cracking and in reducing shrinkage stresses and distortion. This procedure can be applied to welds of plates thicker than 22.5 mm complying with the specific procedures concerning peening tools, temperature range, application area, and other intermediate treatments [215]. Light peening during the application of flame straightening is also employed for the reason that the introduction of compressive stresses decreases the material resistance to the straightening action [207].

The common forms of peening are:

- Shot peening—A machining operation that offers an extensive improvement in the fatigue strength of welded joints. The extent of improvement is dependent on the type of joint and the yield strength of the materials. Shot peening consists of driving the shot (round metallic, glass or ceramic particles), at high velocity, against the area to be treated producing a compressive residual stress in the order of 70%–80% of the yield stress. The shot size is approximately 0.2–1.0 mm depending on the undercuts and interpass notches. The projection velocity should range between 40–60 $\text{m}\cdot\text{s}^{-1}$ [214].
- Hammer peening—A manual technique that decreases the stress concertation at the weld toe by generating a large amount of cold work and changing the radius and angle of the weld toe.
- Ultrasonic impact peening (UIP)—A recently developed technique that uses an ultrasonic hammer to treat the area along the weld toe. A similar mechanism to hammer peening takes place. UIP consists in a single pass of the ultrasonic hammer along the weld toe with a velocity of 0.5 $\text{m}\cdot\text{s}^{-1}$. To produce significant compressive residual stresses, an approximate depth of 0.5–0.7 mm should be achieved.
- Needle peening—Is a technique that is also similar to hammer peening though instead of a solid tool a group of steel wires is used [214].

To improve fatigue performance of welds, it is recommended to execute the procedure of peening until all cracks disappear and the weld toe becomes smooth if cracks are revealed after the conclusion of the first peening passage [216]. To accomplish this smoothness, the intensity of peening should be reduced over time. The transition between the metallic base and the weld should also me smoothed to reduce stress concentration. Additionally, specific procedures may be also necessary depending on the defect being repaired.

Visual inspection of the treated area should be conducted to ensure the treated surface does not have any flaws. NDT, such as MPI, should be employed according to BS EN ISO 17638:2009 [217] and BS EN ISO 23278:2009 [211] or LPT according to BS EN 571-1:1997 [212] and BS EN ISO 23277:2009 [213].

There are some disadvantages to peening such as high levels of noise production and possible exhaustion of the operator/labourer [214].

5. Future Perspectives

As the offshore wind industry expands and near-shore site locations become unavailable, the trend of future OWS projects is to continue expanding further offshore with improved design and to deeper water depths despite project cost implications [4,12]. As project costs and operating lives of OWS increase, corrosion protection will become increasingly important. For corrosion protection coating systems, the research focus is on new environmentally friendly coatings systems with the ability to behave and adapt in response to environmental demands [88,90,93,218]. Coatings with pre-emptive healing abilities will be one of the main targets in the coating industry [97,100,102,103,106,107,219–231]. Combined systems (multilayers) that associate different layers with distinct functions will be improved and/or developed in order to achieve the most efficient protection possible against corrosion [34,37,108,117]. These coatings may be comprised of metal-rich coatings, containing zinc or magnesium particles or other inhibitor particles. There are many epoxy coatings commercially available for corrosion mitigation, but research for contemporaneous polymers or hybrid materials have been gaining market niches. Additionally, several coatings with anti-fouling properties have also been studied. Recently, Palanichamy and Subramanian reported a study where bacteriocin incorporated epoxy based paint exhibited an antifouling property in natural seawater [91]. Azemar et al. recently reported the development of hybrid antifouling paints [89]. The authors reported the use of a copolymer with poly(ε-caprolactone) and poly(dimethylsiloxane) as binder producing a paint that associates hydrophobicity and biodegradable properties. The reported paints prevented fouling settlement and proliferation by erosion, biocides release, and high and constant hydrophobicity [89]. Carteau et al. [90] reported the development of environmentally friendly antifouling paints using biodegradable polymer and lower toxic substances showing that it is possible to obtain antifouling activity with lower toxic substances. Studies using composite coating materials have also been performed [94,96]. According to Gibson and Arun [96] further improvements in the field of deepwater construction using composite materials is necessary in order to improve the performance of offshore industry [96].

The application of the aforementioned studies on coating systems is currently very limited (or nonexistent) in OWSs. Coating systems used in OWSs are typically chosen based on experience and data acquired from offshore oil and gas offshore structures. Therefore, future trends for commercial OWS coatings are predicted to match current research interests such as low cost, pollution-free, self-healing products that are easy to synthesize and apply. The coatings should be effective in corrosion control for long service lives in a wide range of environments [108]. It is clear that studies on the behaviour of innovative coating systems need to be performed in OWSs since scarce information was found by the authors of this paper.

In the near future, Germany and the UK are expected to remain the largest European investors in offshore wind energy with the UK leading the efforts [4,10]. The offshore wind industry is also focused on the development of OWS with higher service life by preventing early fatigue cracks [38,39,52,54,63]. This will be accomplished by testing new alloys and improving the design of the existent OWS as new research becomes available [54].

6. Conclusions

Future OWS will continue to be sited further offshore and in deeper waters. In order for OWS to maintain structural integrity over their design lives, the use of adequate and cost effective coating systems will need to be employed in combination with adequate health monitoring and in-service inspection plans. Germany and the UK are the largest European investors in offshore wind energy and will need to continue to pursue research in these fields to drive down project costs.

Based on the publications gathered in this paper, it can be concluded that most of the coating systems applied on OWS consist of a Zn/Al-metallization, organic pore filler, several intermediate epoxy-based coats and a polyurethane based topcoat. Fundamental corrosion protection measures for OWS typically include:

- Protective coatings and/or cathodic protection;
- Use of a corrosion allowance;
- Inspection/monitoring of corrosion;
- Corrosion-protection-friendly design;
- Control of environment.

Additionally, it can be concluded from the publications found that the offshore wind industry is continuing to grow, but faces several challenges concerning fatigue lives from corrosion and the coupling of aerodynamic and hydrodynamic forces. Early failure of an OWS due to fatigue is a consequence that must be considered during design and inspection phases of a project. Increasing the service life of OWS by preventing early fatigue, testing new alloys and improving design configurations are the main structural engineering focuses of the offshore wind industry.

The complexity related to damage and failure of metallic structures in offshore environments requires the combination of different NDM and DM inspection methods. In order to ensure an accurate assessment using these methods, highly-qualified personnel are necessary. With the technological advances in inspection methods coupled with a better understanding of corrosive environments in recent years, the future is bright for the development of more efficient coating system technologies.

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References

1. Martinez-Luengo, M.; Kolios, A.; Wang, L. Structural health monitoring of offshore wind turbines: A review through the Statistical Pattern Recognition Paradigm. *Renew. Sustain. Energy Rev.* **2016**, *64*, 91–105. [CrossRef]
2. European Comission Earto—Recommendations for Future EU Polies 2014. Available online: http://www.earto.eu/fileadmin/content/04_Newsletter/Newsletter_5_2014/EARTO_Recommendations_for_Future_EU_Innovation_Policy_-_2014.pdf (accessed on 22 April 2016).
3. González, J.S.; Lacal-Arántegui, R. A review of regulatory framework for wind energy in European Union countries: Current state and expected developments. *Renew. Sustain. Energy Rev.* **2016**, *56*, 588–602. [CrossRef]
4. Colmenar-Santos, A.; Perera-Perez, J.; Borge-Diez, D.; de Palacio-Rodríguez, C. Offshore wind energy: A review of the current status, challenges and future development in Spain. *Renew. Sustain. Energy Rev.* **2016**, *64*, 1–18. [CrossRef]
5. EWEA (The European Wind Energy Association). *The European Offshore Wind Industry—Key Trends and Statistics 2011*; Technical Report; EWEA: Bruxelles, Belgium, 2012.
6. EWEA (The European Wind Energy Association). *The European Offshore Wind Industry—Key Trends and Statistics 2012*; Technical Report; EWEA: Bruxelles, Belgium, 2013.
7. EWEA (The European Wind Energy Association). *The European Offshore Wind Industry—Key Trends and Statistics 2013*; Technical Report; EWEA: Bruxelles, Belgium, 2014.
8. EWEA (The European Wind Energy Association). *The European Offshore Wind Industry—Key Trends and Statistics 2014*; Technical Report; EWEA: Bruxelles, Belgium, 2015.
9. EWEA (The European Wind Energy Association). *The European Offshore Wind Industry—Key Trends and Statistics 2015*; Technical Report; EWEA: Bruxelles, Belgium, 2016.
10. Higgins, P.; Foley, A. The evolution of offshore wind power in the United Kingdom. *Renew. Sustain. Energy Rev.* **2014**, *37*, 599–612. [CrossRef]
11. Castro-Santos, L.; Diaz-Casas, V. Sensitivity analysis of floating offshore wind farms. *Energy Convers. Manag.* **2015**, *101*, 271–277. [CrossRef]
12. Rodrigues, S.; Restrepo, C.; Kontos, E.; Teixeira, P.R.; Bauer, P. Trends of offshore wind projects. *Renew. Sustain. Energy Rev.* **2015**, *49*, 1114–1135. [CrossRef]

13. Levitt, A.C.; Kempton, W.; Smith, A.P.; Musial, W.; Firestone, J. Pricing offshore wind power. *Energy Policy* **2011**, *39*, 6408–6421. [CrossRef]
14. Myhr, A.; Bjerkseter, C.; Ågotnes, A.; Nygaard, T.A. Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. *Renew. Energy* **2014**, *66*, 714–728. [CrossRef]
15. Jonkman, J.M.; Matha, D. Dynamics of offshore floating wind turbines—Analysis of three concepts. *Wind Energy* **2011**, *14*, 557–569. [CrossRef]
16. Chen, L.; MacDonald, E. A system-level cost-of-energy wind farm layout optimization with landowner modeling. *Energy Convers. Manag.* **2014**, *77*, 484–494. [CrossRef]
17. Castro-Santos, L.; Diaz-Casas, V. Floating Offshore Wind Farms. In *Green Energy and Technology*; Springer International Publishing: Cham, Switzerland, 2016.
18. Cruz, J.; Atcheson, M. Floating Offshore Wind Energy. In *Green Energy and Technology*; Springer International Publishing: Cham, Switzerland, 2016.
19. Roddier, D.; Cermelli, C.; Aubault, A.; Weinstein, A. WindFloat: A floating foundation for offshore wind turbines. *J. Renew. Sustain. Energy* **2010**, *2*, 33104. [CrossRef]
20. Cermelli, C.; Roddier, D.; Aubault, A. WindFloat: A Floating Foundation for Offshore Wind Turbines—Part II: Hydrodynamics Analysis. In Proceedings of the ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering, Honolulu, HI, USA, 31 May–5 June 2009; pp. 135–143.
21. Aubault, A.; Cermelli, C.; Roddier, D. Parametric Optimization of a Semi-Submersible Platform with Heave Plates. In Proceedings of the ASME 2007 26th International Conference on Offshore Mechanics and Arctic Engineering, San Diego, CA, USA, 10–15 June 2007; pp. 471–478.
22. Principle Power, Inc.—Globalizing Offshore Wind. Available online: http://www.principlepowerinc.com/ (accessed on 10 October 2016).
23. Study to Feasibility of Boundary Conditions for Floating Offshore Wind Turbines. Available online: https://www.researchgate.net/publication/260432811_Study_to_feasibility_of_and_boundary_conditionsfor_floating_offshore_wind_turbines (accessed on 4 February 2017).
24. Portail des Energies de la Mer—Energies de la Mer. Available online: http://www.energiesdelamer.eu/ (accessed on 10 October 2016).
25. Accueil—Nenuphar Wind. Available online: http://www.nenuphar-wind.com/fr/ (accessed on 10 October 2016).
26. WindSea AS—Home. Available online: http://www.windsea.no/ (accessed on 10 October 2016).
27. Lee, K.H. Responses of Floating Wind Turbines to Wind and Wave Excitation. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2005.
28. Pôle Mer Bretagne Atlantique. Available online: http://www.pole-mer-bretagne-atlantique.com/fr/ (accessed on 10 October 2016).
29. Offshore-Windenergie: Fachliche und Technische Herausforderungen: GICON—Großmann Ingenieur Consult GmbH. Available online: http://www.gicon.de/publikationen/fachveroeffentlichungen/veroeffentlichungen/offshore-windenergie-fachliche-und-technische-herausforderungen.html (accessed on 10 October 2016).
30. Statoil—A Leading Energy Company in Oil and Gas Production. Available online: http://www.statoil.com/en/Pages/default.aspx (accessed on 10 October 2016).
31. Njord Floating Wind Power Platform AS | NordicGreen—Nordic Cleantech Scandinavia Startups. Available online: http://www.nordicgreen.net/startups/wind/njord-floating-wind-power-platform (accessed on 10 October 2016).
32. Sway | Changing the Future of Wind Power. Available online: http://www.sway.no/ (accessed on 10 October 2016).
33. A Tribute to Floating Windfarms Corporation. Available online: http://floatingwindfarms.com/index.html (accessed on 10 October 2016).
34. Momber, A. Corrosion and corrosion protection of support structures for offshore wind energy devices (OWEA). *Mater. Corros.* **2011**, *62*, 391–404. [CrossRef]
35. Momber, A.W.; Plagemann, P.; Stenzel, V.; Schneider, M. Investigating Corrosion Protection of Offshore Wind Towers: Part 1: Background and Test Program. *J. Prot. Coat. Linings* **2008**, *30*, 1–14.

36. Momber, A.W.; 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]
37. Mühlberg, K. Corrosion Protection of Offshore Wind Turbines-a Challenge for the Steel Builder and Paint Applicator. *J. Prot. Coat. Linings* **2010**, *20*, 20–27.
38. Adedipe, O.; Brennan, F.; Kolios, A. Review of corrosion fatigue in offshore structures: Present status and challenges in the offshore wind sector. *Renew. Sustain. Energy Rev.* **2016**, *61*, 141–154. [CrossRef]
39. Dong, W.; Moan, T.; Gao, Z. Fatigue reliability analysis of the jacket support structure for offshore wind turbine considering the effect of corrosion and inspection. *Reliab. Eng. Syst. Saf.* **2012**, *106*, 11–27. [CrossRef]
40. Bernhammer, L.O.; van Kuik, G.A.M.; De Breuker, R. Fatigue and extreme load reduction of wind turbine components using smart rotors. *J. Wind Eng. Ind. Aerodyn.* **2016**, *154*, 84–95. [CrossRef]
41. Chew, K.-H.; Tai, K.; Ng, E.Y.K.; Muskulus, M. Analytical gradient-based optimization of offshore wind turbine substructures under fatigue and extreme loads. *Mar. Struct.* **2016**, *47*, 23–41. [CrossRef]
42. Gallego-Calderon, J.; Natarajan, A. Assessment of wind turbine drive-train fatigue loads under torsional excitation. *Eng. Struct.* **2015**, *103*, 189–202. [CrossRef]
43. Herrmann, J.; Rauert, T.; Dalhoff, P.; Sander, M. Fatigue and fracture mechanical behaviour of a wind turbine rotor shaft made of cast iron and forged steel. *Procedia Struct. Integr.* **2016**, *2*, 2951–2958. [CrossRef]
44. Jang, Y.J.; Choi, C.W.; Lee, J.H.; Kang, K.W. Development of fatigue life prediction method and effect of 10-minute mean wind speed distribution on fatigue life of small wind turbine composite blade. *Renew. Energy* **2015**, *79*, 187–198. [CrossRef]
45. Koukoura, C.; Brown, C.; Natarajan, A.; Vesth, A. Cross-wind fatigue analysis of a full scale offshore wind turbine in the case of wind–wave misalignment. *Eng. Struct.* **2016**, *120*, 147–157. [CrossRef]
46. Lee, H.G.; Kang, M.G.; Park, J. Fatigue failure of a composite wind turbine blade at its root end. *Compos. Struct.* **2015**, *133*, 878–885. [CrossRef]
47. Lee, H.G.; Park, J. Static test until structural collapse after fatigue testing of a full-scale wind turbine blade. *Compos. Struct.* **2016**, *136*, 251–257. [CrossRef]
48. Liu, X.; Bo, L.; Luo, H. Dynamical measurement system for wind turbine fatigue load. *Renew. Energy* **2016**, *86*, 909–921. [CrossRef]
49. Nejad, A.R.; Bachynski, E.E.; Kvittem, M.I.; Luan, C.; Gao, Z.; Moan, T. Stochastic dynamic load effect and fatigue damage analysis of drivetrains in land-based and TLP, spar and semi-submersible floating wind turbines. *Mar. Struct.* **2015**, *42*, 137–153. [CrossRef]
50. Tande, J.O.G.; Kvamsdal, T.; Muskulus, M.; Kelma, S.; Schaumann, P. Probabilistic Fatigue Analysis of Jacket Support Structures for Offshore Wind Turbines Exemplified on Tubular Joints. *Energy Procedia* **2015**, *80*, 151–158.
51. Toft, H.S.; Svenningsen, L.; Sørensen, J.D.; Moser, W.; Thøgersen, M.L. Uncertainty in wind climate parameters and their influence on wind turbine fatigue loads. *Renew. Energy* **2016**, *90*, 352–361. [CrossRef]
52. Yeter, B.; Garbatov, Y.; Guedes, S.C. Fatigue damage assessment of fixed offshore wind turbine tripod support structures. *Eng. Struct.* **2015**, *101*, 518–528. [CrossRef]
53. Zhang, M.; Tan, B.; Xu, J. Smart fatigue load control on the large-scale wind turbine blades using different sensing signals. *Renew. Energy* **2016**, *87*(Part 1), 111–119. [CrossRef]
54. Ziegler, L.; Voormeeren, S.; Schafhirt, S.; Muskulus, M. Design clustering of offshore wind turbines using probabilistic fatigue load estimation. *Renew. Energy* **2016**, *91*, 425–433. [CrossRef]
55. Wymore, M.L.; Van Dam, J.E.; Ceylan, H.; Qiao, D. A survey of health monitoring systems for wind turbines. *Renew. Sustain. Energy Rev.* **2015**, *52*, 976–990. [CrossRef]
56. Tajari, M.; Azarsina, F.; Ashrafi, K.N. Nonlinear statics analysis of on offshore jaket platform in the case of explosion. *Int. J. Mar. Sci. Eng.* **2013**, *3*, 33–42.
57. Bertelsen, K.; Erichsen, H.V.; Madsen, S.F. New high current test principle for wind turbine blades simulating the life time impact from lightning discharges. In Proceedings of the International Conference on Lightning and Static Electricity, Paris, France, 28–31 August 2007.
58. Gao, L. Characteristics of Streamer Discharges in Air and Along Insulating Surfaces. Ph.D. Thesis, Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology, University of Uppsala, Uppsala, Sweden, 2000.

59. Rafiei, R.; Mohseni, M.; Yari, H.; Mahdavi, M. Evaluation of degradability of two polyurethane refinish coatings against biological materials: A case study. *Prog. Org. Coat.* **2016**, *93*, 1–10. [CrossRef]
60. Ramezanzadeh, B.; Mohseni, M.; Yari, H. On the electrochemical and structural behaviour of biologically degraded automotive coatings; Part 1: Effect of natural and simulated bird droppings. *Prog. Org. Coat.* **2011**, *71*, 19–31. [CrossRef]
61. Ramezanzadeh, B.; Mohseni, M.; Yari, H.; Sabbaghian, S. An evaluation of an automotive clear coat performance exposed to bird droppings under different testing approaches. *Prog. Org. Coat.* **2009**, *66*, 149–160. [CrossRef]
62. Momber, A.W.; Plagemann, P.; Stenzel, V. Performance and integrity of protective coating systems for offshore wind power structures after three years under offshore site conditions. *Renew. Energy* **2015**, *74*, 606–617. [CrossRef]
63. Adedipe, O.; Brennan, F.; Kolios, A. Corrosion fatigue load frequency sensitivity analysis. *Mar. Struct.* **2015**, *42*, 115–136. [CrossRef]
64. DNVGL-OS-C401. *Fabrication and Testing of Offshore Structures*; DNV GL–Energy: Arnhem, The Netherlands, 2010.
65. DNV-OS-J101. *Design of Offshore Wind Turbine Structures*; DNV GL–Energy: Arnhem, The Netherlands, 2014.
66. DNV-OS-J201. *Offshore Substations for Wind Farms*; DNV GL–Energy: Arnhem, The Netherlands, 2009.
67. Soares, C.G.; Shenoi, R.A. *Seatracker Analysis and Design of Marine Structures*; CRC Press: Boca Raton, FL, USA, 2015.
68. Davis, J.R. *Corrosion Understanding the Basics*; ASM International: Materials Park, OH, USA, 2000.
69. Beech, I.B.; Sunner, J. Biocorrosion: Towards understanding interactions between biofilms and metals. *Curr. Opin. Biotechnol.* **2004**, *15*, 181–186. [CrossRef] [PubMed]
70. Almeida, E.; Diamantino, T.C.; de Sousa, O. Marine paints: The particular case of antifouling paints. *Prog. Org. Coat.* **2007**, *59*, 2–20. [CrossRef]
71. ISO 12944-5:2007. *Paints and Varnishes—Corrosion Protection of Steel Structures by Protective Paint Systems—Part 5: Protective Paint Systems*; ISO: Geneva, Switzerland, 2007.
72. Ault, J.P. The use of coatings for corrosion control on offshore oil structures. *J. Prot. Coat. Linings* **2006**, *23*, 42–47.
73. DNV–OS-C101. *Design of Offshore Steel Structures, General (LRFD Method)*; DNV GL–Energy: Arnhem, The Netherlands, 2011.
74. Momber, A.W. Quantitative performance assessment of corrosion protection systems for offshore wind power transmission platforms. *Renew. Energy* **2016**, *94*, 314–327. [CrossRef]
75. Farrar, C.R.; Worden, K. An introduction to structural health monitoring. *Philos. Trans. R. Soc. Lond. Math. Phys. Eng. Sci.* **2007**, *365*, 303–315. [CrossRef] [PubMed]
76. Farrar, C.R.; Worden, K. Index. In *Structural Health Monitoring*; John Wiley & Sons, Ltd.: New York, NY, USA, 2012; pp. 623–631.
77. Worden, K.; Cross, E.J.; Dervilis, N.; Papatheou, E.; Antoniadou, I. Structural Health Monitoring: From Structures to Systems-of-Systems. *IFAC Pap.* **2015**, *48*, 1–17. [CrossRef]
78. BS 499-1:2009. *Welding Terms and Symbols. Glossary for Welding, Brazing and Thermal Cutting*; BSI: London, UK, 2009.
79. ISO 5817:2014. *Welding—Fusion-Welded Joints in Steel, Nickel, Titanium and Their Alloys (Beam Welding Excluded)—Quality Levels for Imperfections*; ISO (the International Organization for Standardization.): Geneva, Switzerland, 2014.
80. Yusof, F.; Jamaluddin, M.F. 6.07—Welding Defects and Implications on Welded Assemblies A2—Hashmi, Saleem. In *Comprehensive Materials Processing*; Batalha, G.F., Tyne, C.J.V., Yilbas, B., Eds.; Elsevier: Oxford, UK, 2014; pp. 125–134.
81. Kühn, B. Assessment of Existing Steel Structures—Recommendations for Estimation of the Remaining Fatigue Life. *Procedia Eng.* **2013**, *66*, 3–11. [CrossRef]
82. Eurocodes: Building the Future—The European Commission Website on the Eurocodes. Available online: http://eurocodes.jrc.ec.europa.eu/showpublication.php?id=137 (accessed on 19 December 2016).
83. Blondeau, R. *Metallurgy and Mechanics of Welding*; John Wiley & Sons: New York, NY, USA, 2013.

84. Chandler, K.A.; Bayliss, D.A. *Corrosion Protection of Steel Structures*; Elsevier Applied Science Publishers: Amsterdam, The Netherlands, 1985.
85. Lyon, S.B.; Bingham, R.; Mills, D.J. Advances in corrosion protection by organic coatings: What we know and what we would like to know. *Prog. Org. Coat.* **2017**, *102*(Part A), 2–7. [CrossRef]
86. Detty, M.R.; Ciriminna, R.; Bright, F.V.; Pagliaro, M. Xerogel Coatings Produced by the Sol–Gel Process as Anti-Fouling, Fouling-Release Surfaces: From Lab Bench to Commercial Reality. *ChemNanoMat* **2015**, *1*, 148–154. [CrossRef]
87. Trentin, I.; Romairone, V.; Marcenaro, G.; De Carolis, G. Quick test methods for marine antifouling paints. *Prog. Org. Coat.* **2001**, *42*, 15–19. [CrossRef]
88. Detty, M.R.; Ciriminna, R.; Bright, F.V.; Pagliaro, M. Environmentally benign sol-gel antifouling and foul-releasing coatings. *Acc. Chem. Res.* **2014**, *47*, 678–687. [CrossRef] [PubMed]
89. Azemar, F.; Faÿ, F.; Réhel, K.; Linossier, I. Development of hybrid antifouling paints. *Prog. Org. Coat.* **2015**, *87*, 10–19. [CrossRef]
90. Carteau, D.; Vallée-Réhel, K.; Linossier, I.; Quiniou, F.; Davy, R.; Compère, C.; Delbury, M.; Faÿ, F. Development of environmentally friendly antifouling paints using biodegradable polymer and lower toxic substances. *Prog. Org. Coat.* **2014**, *77*, 485–493. [CrossRef]
91. Palanichamy, S.; Subramanian, G. Antifouling properties of marine bacteriocin incorporated epoxy based paint. *Prog. Org. Coat.* **2017**, *103*, 33–39. [CrossRef]
92. Faÿ, F.; Linossier, I.; Peron, J.J.; Langlois, V.; Vallée-Rehel, K. Antifouling activity of marine paints: Study of erosion. *Prog. Org. Coat.* **2007**, *60*, 194–206. [CrossRef]
93. Buskens, P.; Wouters, M.; Rentrop, C.; Vroon, Z. A brief review of environmentally benign antifouling and foul-release coatings for marine applications. *J. Coat. Technol. Res.* **2013**, *10*, 29–36. [CrossRef]
94. Telegdi, J.; Trif, L.; Románszki, L. 5—Smart anti-biofouling composite coatings for naval applications A2. In *Smart Composite Coatings and Membranes*; Woodhead Publishing Series in Composites Science and Engineering; Montemor, M.F., Ed.; Woodhead Publishing: Cambridge, UK, 2016; pp. 123–155.
95. Torabinejad, V.; Aliofkhazraei, M.; Assareh, S.; Allahyarzadeh, M.H.; Rouhaghdam, A.S. Electrodeposition of Ni-Fe alloys, composites, and nano coatings–A review. *J. Alloys Compd.* **2017**, *691*, 841–859. [CrossRef]
96. Gibson, A.G.; Arun, S. Composite Materials in the Offshore Industry. In *Reference Module in Materials Science and Materials Engineering*; Elsevier: Amsterdam, The Netherlands, 2016.
97. Cho, S.H.; White, S.R.; Braun, P.V. Self-Healing Polymer Coatings. *Adv. Mater.* **2009**, *21*, 645–649. [CrossRef]
98. Carneiro, J.; Tedim, J.; Fernandes, S.C.M.; Freire, C.S.R.; Silvestre, A.J.D.; Gandini, A.; Ferreira, M.G.S.; Zheludkevich, M.L. Chitosan-based self-healing protective coatings doped with cerium nitrate for corrosion protection of aluminum alloy 2024. *Prog. Org. Coat.* **2012**, *75*, 8–13. [CrossRef]
99. Yoganandan, G.; Pradeep, P.K.; Balaraju, J.N. Evaluation of corrosion resistance and self-healing behavior of zirconium–cerium conversion coating developed on AA2024 alloy. *Surf. Coat. Technol.* **2015**, *270*, 249–258. [CrossRef]
100. Lutz, A.; Mol, J.M.C.; De Graeve, I.; Terryn, H. 6—Smart corrosion protection by multi-action self-healing polymeric coatings A2. In *Smart Composite Coatings and Membranes*; Woodhead Publishing Series in Composites Science and Engineering; Montemor, M.F., Ed.; Woodhead Publishing: Cambridge, UK, 2016; pp. 157–181.
101. Alaneme, K.K.; Bodunrin, M.O. Self-healing using metallic material systems—A review. *Appl. Mater. Today* **2017**, *6*, 9–15. [CrossRef]
102. Montemor, M.F. Hybrid nanocontainer-based smart self-healing composite coatings for the protection of metallic assets. In *Smart Composite Coatings and Membranes*; Woodhead Publishing Series in Composites Science and Engineering; Meng, H., Ed.; Woodhead Publishing: Cambridge, UK, 2016; pp. 183–209.
103. Hughes, A.E. Self-healing coatings A2. In *Recent Advances in Smart Self-healing Polymers and Composites*; Woodhead Publishing Series in Composites Science and Engineering; Li, G.Q., Ed.; Woodhead Publishing: Cambridge, UK, 2015; pp. 211–241.
104. Montemor, M.F. Functional and smart coatings for corrosion protection: A review of recent advances. *Surf. Coat. Technol.* **2014**, *258*, 17–37. [CrossRef]

105. Plawecka, M.; Snihirova, D.; Martins, B.; Szczepanowicz, K.; Warszynski, P.; Montemor, M.F. Self healing ability of inhibitor-containing nanocapsules loaded in epoxy coatings applied on aluminium 5083 and galvanneal substrates. *Electrochim. Acta* **2014**, *140*, 282–293. [CrossRef]
106. Mittal, V. Self-healing anti-corrosion coatings for applications in structural and petrochemical engineering A2. In *Handbook of Smart Coatings for Materials Protection*; Makhlouf, A.S.H., Ed.; Woodhead Publishing: Cambridge, UK, 2014; pp. 183–197.
107. Thakur, V.K.; Kessler, M.R. Self-healing polymer nanocomposite materials: A review. *Polymer* **2015**, *69*, 369–383. [CrossRef]
108. Figueira, R.B.; Fontinha, I.R.; Silva, C.J.R.; Pereira, E.V. Hybrid Sol-Gel Coatings: Smart and Green Materials for Corrosion Mitigation. *Coatings* **2016**, *6*, 12. [CrossRef]
109. Pandey, S.; Mishra, S.B. Sol–gel derived organic–inorganic hybrid materials: Synthesis, characterizations and applications. *J. Sol-Gel Sci. Technol.* **2011**, *59*, 73–94. [CrossRef]
110. Han, Y.-H.; Taylor, A.; Mantle, M.D.; Knowles, K.M. UV curing of organic–inorganic hybrid coating materials. *J. Sol-Gel Sci. Technol.* **2007**, *43*, 111–123. [CrossRef]
111. Gilberts, J.; Tinnemans, A.H.A.; Hogerheide, M.P.; Koster, T.P.M. UV Curable Hard Transparent Hybrid Coating Materials on Polycarbonate Prepared by the Sol-Gel Method. *J. Sol-Gel Sci. Technol.* **1998**, *11*, 153–159. [CrossRef]
112. Sayilkan, H.; Şener, Ş.; Şener, E. The Sol-Gel Synthesis and Application of Some Anticorrosive Coating Materials. *Mater. Sci.* **2003**, *39*, 106–110. [CrossRef]
113. Ciriminna, R.; Fidalgo, A.; Pandarus, V.; Béland, F.; Ilharco, L.M.; Pagliaro, M. The Sol-Gel Route to Advanced Silica-Based Materials and Recent Applications. *Chem. Rev.* **2013**, *113*, 6592–6620. [CrossRef] [PubMed]
114. Wilkes, G.L.; Orler, B.; Huang, H.H. "Ceramers": Hybrid materials incorporating polymeric/oligomeric species into inorganic glasses utilizing a sol-gel approach. *Polym. Prep.* **1985**, *26*, 300–302.
115. Arkhireeva, A.; Hay, J.N.; Lane, J.M.; Manzano, M.; Masters, H.; Oware, W.; Shaw, S.J. Synthesis of Organic-Inorganic Hybrid Particles by Sol-Gel Chemistry. *J. Sol-Gel Sci. Technol.* **2004**, *31*, 31–36. [CrossRef]
116. Innocenzi, P.; Kidchob, T.; Yoko, T. Hybrid Organic-Inorganic Sol-Gel Materials Based on Epoxy-Amine Systems. *J. Sol-Gel Sci. Technol.* **2005**, *35*, 225–235. [CrossRef]
117. Figueira, R.B.; Silva, C.J.R.; Pereira, E.V. Organic–inorganic hybrid sol–gel coatings for metal corrosion protection: A review of recent progress. *J. Coat. Technol. Res.* **2014**, *12*, 1–35. [CrossRef]
118. Figueira, R.B.; Silva, C.J.R.; Pereira, E.V. Hybrid sol–gel coatings for corrosion protection of hot-dip galvanized steel in alkaline medium. *Surf. Coat. Technol.* **2015**, *265*, 191–204. [CrossRef]
119. Figueira, R.B.; Silva, C.J.; Pereira, E.V.; Salta, M.M. Alcohol-Aminosilicate Hybrid Coatings for Corrosion Protection of Galvanized Steel in Mortar. *J. Electrochem. Soc.* **2014**, *161*, C349–C362. [CrossRef]
120. Carneiro, J.; Tedim, J.; Ferreira, M.G.S. Chitosan as a smart coating for corrosion protection of aluminum alloy 2024: A review. *Prog. Org. Coat.* **2015**, *89*, 348–356. [CrossRef]
121. Dias, S.A.S.; Lamaka, S.V.; Nogueira, C.A.; Diamantino, T.C.; Ferreira, M.G.S. Sol–gel coatings modified with zeolite fillers for active corrosion protection of AA2024. *Corros. Sci.* **2012**, *62*, 153–162. [CrossRef]
122. Mai, T. Technology Readiness Level. Available online: http://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html (accessed on 9 January 2017).
123. Frei, R.; McWilliam, R.; Derrick, B.; Purvis, A.; Tiwari, A.; Serugendo, G.D.M. Self-healing and self-repairing technologies. *Int. J. Adv. Manuf. Technol.* **2013**, *69*, 1033–1061. [CrossRef]
124. Steelwork Corrosion Control. Available online: https://www.crcpress.com/Steelwork-Corrosion-Control/Bayliss-Deacon/p/book/9780415261012 (accessed on 23 August 2016).
125. Buchheit, R.G. Chapter 18—Corrosion resistant coatings and paints. In *Handbook of Environmental Degradation of Materials*; Kutz, M., Ed.; William Andrew Publishing: Norwich, NY, USA, 2005; pp. 367–385.
126. Mostafaei, A.; Nasirpouri, F. Epoxy/polyaniline–ZnO nanorods hybrid nanocomposite coatings: Synthesis, characterization and corrosion protection performance of conducting paints. *Prog. Org. Coat.* **2014**, *77*, 146–159. [CrossRef]
127. Coso, E.B. *Trends in Electrochemistry and Corrosion at the Beginning of the 21st Century: Dedicated to Professor Dr. Josep M. Costa on the Occasion of His 70th Birthday*; Edicions Universitat Barcelona: Barcelona, Spain, 2004.
128. New System Painting & Decorating Ltd. Homepage. Available online: http://www.manta.com/ic/mt6htfp/ca/new-system-painting-decorating-ltd (accessed on 26 August 2016).

129. Paint and Coatings Industry Overview—Chemical Economics Handbook (CEH) | HIS. Available online: https://www.ihs.com/products/paint-and-coatings-industry-chemical-economics-handbook.html (accessed on 26 August 2016).
130. BS EN ISO 3549:2002. *Zinc Dust Pigments for Paints, Specifications and Test Methods*; BSI: London, UK, 2002.
131. ASTM D520-00(2011). *Standard Specification for Zinc Dust Pigment*; ASTM International: West Conshohocken, PA, USA, 2011.
132. Sahoo, P.; Das, S.K.; Paulo, D.J. Surface Finish Coatings A2. In *Comprehensive Materials Finishing*; Hashmi, M.S.J., Ed.; Elsevier: Oxford, UK, 2017; pp. 38–55.
133. Jain, R.; Wasnik, M.; Sharma, A.; Kr Bhadu, M.; Rout, T.K.; Khanna, A.S. Development of Epoxy Based Surface Tolerant Coating Improvised with Zn Dust and MIO on Steel Surfaces. *J. Coat.* **2014**, *2014*, 1–15. [CrossRef]
134. Roselli, S.N.; del Amo, B.; Carbonari, R.O.; Di Sarli, A.R.; Romagnoli, R. Painting rusted steel: The role of aluminum phosphosilicate. *Corros. Sci.* **2013**, *74*, 194–205. [CrossRef]
135. Singh, D.D.N.; Bhattacharya, D. Performance and mechanism of action of self-priming organic coating on oxide covered steel surface. *Prog. Org. Coat.* **2010**, *68*, 62–69. [CrossRef]
136. ISO 12944-1:1998(en). *Paints and Varnishes—Corrosion Protection of Steel Structures by Protective Paint Systems—Part 1: General Introduction*; ISO: Geneva, Switzerland, 1998.
137. ISO 20340:2009. *Paints and Varnishes—Performance Requirements for Protective Paint Systems for Offshore and Related Structures*. Available online: http://www.iso.org/iso/catalogue_detail.htm?csnumber=44180 (accessed on 29 September 2016).
138. M-501 Norsok Standard. *Surface preparation and protective coating*; Standards Norway: Lysaker, Norway, 2012.
139. The Resource for the Global Coatings Industry—Coatings World. Available online: http://www.coatingsworld.com/ (accessed on 26 October 2016).
140. Kjærside, S.B. Surface protection and coatings for wind turbine rotor blades. In *Advances in Wind Turbine Blade Design and Materials*; Woodhead Publishing Series in Energy; Woodhead Publishing: Cambridge, UK, 2013; pp. 387–412.
141. Wijewardane, S. Thermal spray coatings in renewable energy applications A2—. In *Future Development of Thermal Spray Coatings*; Espallargas, N., Ed.; Woodhead Publishing: Cambridge, UK, 2015; pp. 241–257.
142. Shi, H.; Liu, F.; Han, E.-H. The corrosion behavior of zinc-rich paints on steel: Influence of simulated salts deposition in an offshore atmosphere at the steel/paint interface. *Surf. Coat. Technol.* **2011**, *205*, 4532–4539. [CrossRef]
143. Momber, A.W.; Irmer, M.; Glück, N. Performance characteristics of protective coatings under low-temperature offshore conditions. Part 1: Experimental set-up and corrosion protection performance. *Cold Reg. Sci. Technol.* **2016**, *127*, 76–82. [CrossRef]
144. Momber, A.W.; Irmer, M.; Glück, N. Performance characteristics of protective coatings under low-temperature offshore conditions. Part 2: Surface status, hoarfrost accretion and mechanical properties. *Cold Reg. Sci. Technol.* **2016**, *127*, 109–114. [CrossRef]
145. Wind Protection Tapes: Wind Turbine Blade Repair: 3M Renewable Energy. Available online: http://solutions.3m.com/wps/portal/3M/en_US/Wind/Energy/Products/Wind_Protection_Tapes/ (accessed on 28 September 2016).
146. Valaker, E.A.; Armada, S.; Wilson, S. Droplet Erosion Protection Coatings for Offshore Wind Turbine Blades. *Energy Procedia* **2015**, *80*, 263–275. [CrossRef]
147. ISO 12944-7:1998. *Paints and Varnishes—Corrosion Protection of Steel Structures by Protective Paint Systems—Part 7: Execution and Supervision of Paint Work*; ISO: Geneva, Switzerland, 1998.
148. Shi, H.; Liu, F.; Han, E.-H. The corrosion behavior of zinc-rich paints on steel Influence of simulated salts deposition in an offshore atmosphere at the steel paint interface. *Surf. Coat. Technol.* **2011**, *205*, 4532–4539. [CrossRef]
149. Black, A.R.; Mathiesen, T.; Hilbert, L.R. *Corrosion Protection of Offshore wind Foundations*; NACE International: Houston, TX, USA, 2015.
150. Corrosion Risks and Mitigation Strategies for Offshore Wind Turbine Foundations. Available online: http://www.materialsperformance.com/articles/material-selection-design/2016/03/corrosion-risks-and-mitigation-strategies-for-offshore-wind-turbine-foundations (accessed on 26 October 2016).
151. Porter, F.C. *Corrosion Resistance of Zinc and Zinc Alloys*; CRC Press: Boca Raton, FL, USA, 1994.

152. Figueira, R.B.; Silva, C.J.R.; Pereira, E.V.; Salta, M.M. Corrosion of Hot-Dip Galvanized Steel Reinforcement. *Corros. E Prot. Mater.* **2014**, *33*, 51–61.
153. ISO 14713-2:2009. *Zinc Coatings—Guidelines and Recommendations for the Protection against Corrosion of Iron and Steel in Structures—Part 2: Hot Dip Galvanizing*; ISO: Geneva, Switzerland, 2009.
154. ISO 14713-1:2009. *Zinc Coatings—Guidelines and Recommendations for the Protection against Corrosion of Iron and Steel in Structures—Part 1: General Principles of Design and Corrosion Resistance*; ISO: Geneva, Switzerland, 2009.
155. ISO 27831-1:2008. *Metallic and Other Inorganic Coatings—Cleaning and Preparation of Metal Surfaces—Part 1: Ferrous Metals and Alloys*; ISO: Geneva, Switzerland, 2008.
156. BS EN 1403:1998. *Corrosion Protection of Metals. Electrodeposited Coatings. Method of Specifying General Requirements*; BSI: London, UK, 1998.
157. BS EN ISO 2081:2008. *Metallic and Other Inorganic Coatings. Electroplated Coatings of Zinc with Supplementary Treatments on Iron or Steel*; BSI: London, UK, 2008.
158. BS EN 657:2005. *Thermal Spraying. Terminology, Classification*; BSI: London, UK, 2005.
159. IBS EN 14616:2004. *Thermal Spraying. Recommendations for Thermal Spraying*; BSI: London, UK, 2004.
160. ISO 2063:2005. *Thermal Spraying—Metallic and Other Inorganic Coatings—Zinc, Aluminium and Their Alloys*; ISO: Geneva, Switzerland, 2005.
161. BS EN 13507:2010. *Thermal Spraying. Pre-Treatment of Surfaces of Metallic Parts and Components for thermal Spraying*; BSI: London, UK, 2010.
162. ISO 14713-3:2009. *Zinc Coatings—Guidelines and Recommendations for the Protection against Corrosion of Iron and Steel in Structures—Part 3: Sherardizing*; ISO: Geneva, Switzerland, 2009.
163. BS EN 13811:2003. *Sherardizing. Zinc Diffusion Coatings on Ferrous Products. Specification*; BSI: London, UK, 2003.
164. ISO 2859-1:1999. *Sampling Procedures for Inspection by Attributes—Part 1: Sampling Schemes Indexed by Acceptance Quality Limit (AQL) for Lot-by-Lot Inspection*; ISO: Geneva, Switzerland, 1999.
165. ISO 2859-3:2005. *Sampling Procedures for Inspection by Attributes—Part 3: Skip-Lot Sampling Procedures*; ISO: Geneva, Switzerland, 2005.
166. ISO 2178:2016. *Non-Magnetic Coatings on Magnetic Substrates—Measurement of Coating Thickness—Magnetic Method*; ISO: Geneva, Switzerland, 2016.
167. BS EN ISO 1460:1995. *Metallic Coatings. Hot Dip Galvanized Coatings on Ferrous Materials. Gravimetric Determination of the Mass per Unit Area*; BSI: London, UK, 1995.
168. ISO 12944-2:1998. *Paints and Varnishes—Corrosion Protection of Steel Structures by Protective Paint Systems—Part 2: Classification of Environments*; ISO: Geneva, Switzerland, 1998.
169. ISO 12944-4:1998. *Paints and Varnishes—Corrosion Protection of Steel Structures by Protective Paint Systems—Part 4: Types of Surface and Surface Preparation*; ISO: Geneva, Switzerland, 1998.
170. ISO 8504-2:2000. *Preparation of Steel Substrates before Application of Paints and Related Products—Surface Preparation Methods—Part 2: Abrasive Blast-Cleaning*; ISO: Geneva, Switzerland, 2000.
171. BS EN ISO 8502-4:2000. *Preparation of Steel Substrates before Application of Paints and Related Products. Tests for the Assessment of Surface Cleanliness. Guidance on the Estimation of the Probability of Condensation Prior to Paint Application*; BSI: London, UK, 2000.
172. Acceleration of Amine-Cured Epoxy Resin Systems. Available online: http://www.huntsman.com/performance_products/Media%20Library/a_MC348531CFA3EA9A2E040EBCD2B6B7B06/Home_MC348531CFA8BA9A2E040EBCD2B6B7B06/Technical%20Presentati_MC4296668862CCC36E040EBCD2B6B5BA5/files/Acceleration%20of%20Epoxy%20Resin%20Systems%20-%20Burton%20-%20Rev%202006.pdf (accessed on 26 October 2016).
173. ISO 2808:2007. *Paints and Varnishes—Determination of Film Thickness*; ISO: Geneva, Switzerland, 2007.
174. ISO 4624:2002. *Paints and Varnishes—Pull-Off Test for Adhesion*; ISO: Geneva, Switzerland, 2002.
175. ISO 19840:2004. *Paints and Varnishes—Corrosion Protection of Steel Structures by Protective Paint Systems—Measurement of, and Acceptance criteria for, the Thickness of dry Films on Rough Surfaces*; ISO: Geneva, Switzerland, 2004.
176. Czichos, H.; Saito, T.; Smith, L.E. *Springer Handbook of Metrology and Testing*; Springer Science & Business Media: Berlin, Germany, 2011.
177. BS EN 13018:2001. *Non-Destructive Testing. Visual Testing. General Principles*; BSI: London, UK, 2001.

178. García-Martín, J.; Gómez-Gil, J.; Vázquez-Sánchez, E. Non-Destructive Techniques Based on Eddy Current Testing. *Sensors* **2011**, *11*, 2525–2565. [CrossRef] [PubMed]
179. Jiao, S.; Cheng, L.; Li, X.; Li, P.; Ding, H. Monitoring fatigue cracks of a metal structure using an eddy current sensor. *EURASIP J. Wirel. Commun. Netw.* **2016**, *1*, 188. [CrossRef]
180. Palanisamy, R.; Lakin, K.M. Development of an Eddy Current Inspection Technique for Sleeved Engine Disk Bolt Holes. In *Review of Progress in Quantitative Nondestructive Evaluation*; Library of Congress Cataloging in Publication Data; Thompson, D.O., Chimenti, D.E., Eds.; Springer: New York, NY, USA, 1983; pp. 205–223.
181. Cleland, D. *Ultrasonic Methods of Non-Destructive Testing*; Wiley-Blackwell: Oxford, UK, 2011.
182. Dutta, D. *Ultrasonic Techniques for Baseline-Free Damage Detection in Structures*; Carnegie Mellon University: Pittsburgh, PA, USA, 2010.
183. Chen, C.H. *Ultrasonic and Advanced Methods for Nondestructive Testing and Material Characterization*; World Scientific: Singapore, Singapore, 2007.
184. European Commission. CORDIS: Publications. Final Report—OPCOM (Development of Ultrasonic Guided Wave Inspection Technology for the Condition Monitoring of Offshore Structures). Available online: http://cordis.europa.eu/publication/rcn/12381_en.html (accessed on 21 October 2016).
185. European Commission. CORDIS: Projects & Results Service. Novel Non-Destructive Testing of Offshore Structures. Available online: http://cordis.europa.eu/result/rcn/88583_en.html (accessed on 21 October 2016).
186. Upadhyay, V.; Battocchi, D. Localized electrochemical characterization of organic coatings: A brief review. *Prog. Org. Coat.* **2016**, *99*, 365–377. [CrossRef]
187. Stratmann, M.; Streckel, H.; Feser, R. A new technique able to measure directly the delamination of organic polymer films. *Corros. Sci.* **1991**, *32*, 467–470. [CrossRef]
188. ASTM G59–97(2014). *Standard Test Method for Conducting Potentiodynamic Polarization Resistance Measurements*; ASTM International: West Conshohocken, PA, USA, 2014.
189. Grauer, R.; Moreland, P.J.; Pini, G. *A Literature Review of Polarization Resistance Constant (B) Values for the Measurement of Corrosion Rate*; National Association of Corrosion Engineers: Houston, TE, USA, 1982.
190. Figueira, R.B.; Silva, C.J.R.; Pereira, E.V. Hybrid sol–gel coatings for corrosion protection of galvanized steel in simulated concrete pore solution. *J. Coat. Technol. Res.* **2016**, *13*, 1–19. [CrossRef]
191. Kiruthika, P.; Subasri, R.; Jyothirmayi, A.; Sarvani, K.; Hebalkar, N.Y. Effect of plasma surface treatment on mechanical and corrosion protection properties of UV-curable sol-gel based GPTS-ZrO_2 coatings on mild steel. *Surf. Coat. Technol.* **2010**, *204*, 1270–1276. [CrossRef]
192. Ahmad, S.; Zafar, F.; Sharmin, E.; Garg, N.; Kashif, M. Synthesis and characterization of corrosion protective polyurethanefattyamide/silica hybrid coating material. *Prog. Org. Coat.* **2012**, *73*, 112–117. [CrossRef]
193. Amirudin, A.; Thieny, D. Application of electrochemical impedance spectroscopy to study the degradation of polymer-coated metals. *Prog. Org. Coat.* **1995**, *26*, 1–28. [CrossRef]
194. Arthanareeswari, M.; Narayanan, T.S.N.S.; Kamaraj, P.; Tamilselvi, M. Polarization and impedance studies on zinc phosphate coating developed using galvanic coupling. *J. Coat. Technol. Res.* **2012**, *9*, 39–46. [CrossRef]
195. Barsoukov, E.; Macdonald, J.R. *Impedance Spectroscopy: Theory, Experiment, and Applications*; Wiley: New York, NY, USA, 2005.
196. Castela, A.S.; Simões, A.M. An impedance model for the estimation of water absorption in organic coatings. Part I: A linear dielectric mixture equation. *Corros. Sci.* **2003**, *45*, 1631–1646. [CrossRef]
197. Orazem, M.E.; Tribollet, B. *Electrochemical Impedance Spectroscopy*; Wiley: New York, NY, USA, 2008.
198. Hamlaoui, Y.; Pedraza, F.; Tifouti, L. Comparative study by electrochemical impedance spectroscopy (EIS) on the corrosion resistance of industrial and laboratory zinc coatings. *Am. J. Appl. Sci.* **2007**, *4*, 430. [CrossRef]
199. Figueira, R.B.; Silva, C.J.; Pereira, E.V. Ureasilicate Hybrid Coatings for Corrosion Protection of Galvanized Steel in Chloride-Contaminated Simulated Concrete Pore Solution. *J. Electrochem. Soc.* **2015**, *162*, C666–C676. [CrossRef]
200. Figueira, R.B.; Silva, C.J.; Pereira, E.V.; Salta, M.M. Ureasilicate Hybrid Coatings for Corrosion Protection of Galvanized Steel in Cementitious Media. *J. Electrochem. Soc.* **2013**, *160*, C467–C479. [CrossRef]
201. Rosero-Navarro, N.C.; Pellice, S.A.; Castro, Y.; Aparicio, M.; Durán, A. Improved corrosion resistance of AA2024 alloys through hybrid organic–inorganic sol–gel coatings produced from sols with controlled polymerisation. *Surf. Coat. Technol.* **2009**, *203*, 1897–1903. [CrossRef]

202. Bastos, A.C.; Ferreira, M.G.S.; Simões, A.M.P. The uneven corrosion of deep drawn coil-coatings investigated by EIS. *Electrochimica Acta* **2011**, *56*, 7825–7832. [CrossRef]
203. Fayyad, E.M.; Almaadeed, M.A.; Jones, A.; Abdullah, A.M. Evaluation techniques for the corrosion resistance of self-healing coatings. *Int. J. Electrochem. Sci.* **2014**, *9*, 4989–5011.
204. Figueira, R.B.; Silva, C.J.R.; Pereira, E.V. Influence of Experimental Parameters Using the Dip-Coating Method on the Barrier Performance of Hybrid Sol-Gel Coatings in Strong Alkaline Environments. *Coatings* **2015**, *5*, 124–141. [CrossRef]
205. BS EN 1993-1-9:2005. *Eurocode 3. Design of Steel Structures. Fatigue*; BSI: London, UK, 2005.
206. Fatigue Design of Offshore Steel Structures—RP-C203. Available online: https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2011-10/RP-C203.pdf (accessed on 4 February 2017).
207. Welded Repair of Cracks in Steel Bridge Members. Available online: http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_rpt_321.pdf (accessed on 20 December 2016).
208. Chen, W.-F.; Duan, L. *Bridge Engineering Handbook, Second Edition: Construction and Maintenance*; CRC Press: Boca Raton, FL, USA, 2014.
209. Bai, Q.; Bai, Y. 32—Welding and Defect Acceptance. In *Subsea Pipeline Design, Analysis, and Installation*; Gulf Professional Publishing: Boston, MA, USA, 2014; pp. 695–705.
210. ISO 17635:2003. *Non-Destructive Testing of Welds—General Rules for Fusion Welds in Metallic Materials*; ISO: Geneva, Switzerland, 2003.
211. BS EN ISO 23278:2009. *Non-Destructive Testing of Welds. Magnetic Particle Testing of Welds*; BSI: London, UK, 2009.
212. BS EN 571-1:1997. *Non-Destructive Testing. Penetrant Testing. General Principles—BSI British Standards*; BSI: London, UK, 1997.
213. BS EN ISO 23277:2009. *Non-Destructive Testing of Welds. Penetrant Testing of Welds. Acceptance levels*; BSI: London, UK, 2009.
214. Kirkhope, K.J.; Bell, R.; Caron, L.; Basu, R.I.; Ma, K.-T. Weld detail fatigue life improvement techniques. Part 1: Review. *Mar. Struct.* **1999**, *12*, 447–474. [CrossRef]
215. Guidelines for Evaluation and Repair of Damaged Steel Bridge Members. Available online: https://trid.trb.org/view.aspx?id=208887 (accessed on 4 February 2017).
216. Design of Hydraulic Steel Structures. Available online: http://www.publications.usace.army.mil/Portals/76/Publications/EngineerTechnicalLetters/ETL_1110-2-584.pdf (accessed on 20 December 2016).
217. BS EN ISO 17638:2009. *Non-Destructive Testing of Welds. Magnetic Particle Testing—BSI British Standards*; BSI: London, UK, 2009.
218. Iroh, J.O.; Rajamani, D. Synthesis and Structure of Environmentally Friendly Hybrid Clay/Organosilane Nanocomposite Coatings. *J. Inorg. Organomet. Polym. Mater.* **2012**, *22*, 595–603. [CrossRef]
219. Yan, T.; Xu, S.; Peng, Q.; Zhao, L.; Zhao, X.; Lei, X.; Zhang, F. Self-Healing of Layered Double Hydroxide Film by Dissolution/Recrystallization for Corrosion Protection of Aluminum. *J. Electrochem. Soc.* **2013**, *160*, C480–C486. [CrossRef]
220. Urdl, K.; Kandelbauer, A.; Kern, W.; Müller, U.; Thebault, M.; Zikulnig-Rusch, E. Self-healing of densely crosslinked thermoset polymers—A critical review. *Prog. Org. Coat.* **2017**, *104*, 232–249. [CrossRef]
221. LIN, B.; LU, J. Self-healing mechanism of composite coatings obtained by phosphating and silicate sol post-sealing. *Trans. Nonferrous Met. Soc. China* **2014**, *24*, 2723–2728. [CrossRef]
222. Aramaki, K. Self-healing mechanism of an organosiloxane polymer film containing sodium silicate and cerium(III) nitrate for corrosion of scratched zinc surface in 0.5 M NaCl. *Corros. Sci.* **2002**, *44*, 1621–1632. [CrossRef]
223. Ghosh, S.K. *Self-Healing Materials: Fundamentals, Design Strategies, and Applications*; Wiley: New York, NY, USA, 2009.
224. Arunchandran, C.; Ramya, S.; George, R.P.; Mudali, U.K. Self-Healing Corrosion Resistive Coatings Based on Inhibitor Loaded TiO_2 Nanocontainers. *J. Electrochem. Soc.* **2012**, *159*, C552–C559. [CrossRef]
225. García, S.J.; Fischer, H.R.; White, P.A.; Mardel, J.; González-García, Y.; Mol, J.M.C.; Hughes, A.E. Self-healing anticorrosive organic coating based on an encapsulated water reactive silyl ester: Synthesis and proof of concept. *Prog. Org. Coat.* **2011**, *70*, 142–149. [CrossRef]
226. Abdolah, Z.M.; van der Zwaag, S.; Garcia, S.J. Routes to extrinsic and intrinsic self-healing corrosion protective sol-gel coatings: A review. *Self-Heal. Mater.* **2013**, *1*, 1–18. [CrossRef]

227. Fan, S.; Zhang, L.; Cheng, L.; Xu, Y.; Yao, N. Preparation and Properties of Self-Healing Coating for C/SiC Brake Materials. *Int. J. Appl. Ceram. Technol.* **2008**, *5*, 204–209. [CrossRef]
228. Blaiszik, B.J.; Sottos, N.R.; White, S.R. Nanocapsules for self-healing materials. *Compos. Sci. Technol.* **2008**, *68*, 978–986. [CrossRef]
229. Montemor, M.F.; Snihirova, D.V.; Taryba, M.G.; Lamaka, S.V.; Kartsonakis, I.A.; Balaskas, A.C.; Kordas, G.C.; Tedim, J.; Kuznetsova, A.; Zheludkevich, M.L.; et al. Evaluation of self-healing ability in protective coatings modified with combinations of layered double hydroxides and cerium molibdate nanocontainers filled with corrosion inhibitors. *Electrochim. Acta* **2012**, *60*, 31–40. [CrossRef]
230. Hughes, A.E.; Cole, I.S.; Muster, T.H.; Varley, R.J. Designing green, self-healing coatings for metal protection. *NPG Asia Mater.* **2010**, *2*, 143–151. [CrossRef]
231. Zheludkevich, M.L.; Shchukin, D.G.; Yasakau, K.A.; Möhwald, H.; Ferreira, M.G.S. Anticorrosion Coatings with Self-Healing Effect Based on Nanocontainers Impregnated with Corrosion Inhibitor. *Chem. Mater.* **2007**, *19*, 402–411. [CrossRef]