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ARTICLE

Materials and Corrosion

Root causes for corrosion on painted steel structures in marine environments

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Abstract

Our understanding of the failure mechanisms of coatings, for example, cathodic disbonding, corrosion creep, blistering, and cracking, have been developed to a high level over the past decades. However, knowing what actually causes coatings to fail in the field is also important. Several atmospheric field tests of coating with duration 2–9 years have been published, showing that epoxy-based heavy-duty protective coating systems with zinc-rich primers have high resistance against corrosion creep from damages in the coating. Despite this, scribe creep corrosion has become the most important evaluation parameter in standardized testing. In this work, inspection pictures from an offshore oil and gas platform, a ballast water tank system, and two coastal road bridges have been analyzed with respect to the root cause for initiation of corrosion on coated steel. The results show that corrosion mainly initiates at edges and welds. Between 50% and 90% of the corrosion attacks could be attributed to this, depending on the type of structure. The paint failed due to low film thickness, that is, the wet paint retracts from sharp edges in the surface so that the cured film has reduced barrier properties.

KEYWORDS
coating failure, corrosion, marine environment, protective coatings

1 | INTRODUCTION

Most steel structures exposed in the marine atmosphere are protected by organic coatings. Hence, the safety and durability of these structures depend on the integrity of the organic coatings. The total coated area of an offshore wind turbine, steel bridge, large ship, or offshore wind energy farm can be from ten thousand square meters to several hundred thousand square meters. Given a combination of large surface area and long structure lifetime, inspection and maintenance of the protective coating system are major contributors to the operational expenses.[1] For example, on offshore wind turbines, coating repair costs are estimated to be 100 times higher than the costs for the initial application of the coating mainly due to the challenging access.[2] Coating systems with long protective durability are therefore of great interest.

Coating lifetime is defined as the time to the first major maintenance operation, according to ISO 12944-1.[3] In part 9, the standard specifies the required test regimes and evaluation methods to be employed when prequalifying coating systems for marine and offshore conditions.[4] With these standardized test protocols, scribe creep corrosion has become the most important evaluation parameter for qualification of coating systems. However, field testing indicates that a shift in focus may be beneficial. Several coating field tests with duration 2–9 years have been published, showing that epoxy-based protective coating systems with zinc-rich primers have high resistance against corrosion creep from damages in the coating.[5–8] Still, coating lifetime of such coating systems has been indicated to be at 8–15 years.[9] Aging of a coating depends on the exposure environment, but epoxy-based protective coating systems for example, three-coat paint systems with a zinc epoxy primer as qualified according to NORSOK M-501, System 1[9] are not expected to fail due to aging within this time scale. Hence, it is reasonable to assume that the failures that result in the need for maintenance after 8–15 years are caused by application errors and not aging.

The wet paint is a semiproduct, and the final coating is produced (i.e., applied) at the yard during construction, or in the field during maintenance. Failure of a coating product with a proven track record can be due to deviation in the paint composition, errors during surface pretreatment or application, wrong specifications of coating, mechanical, chemical or physical overload in use, or aging. Production of the paint in the factory is carefully monitored, so coating failure is rarely caused by errors or deviations in the paint itself.[10] Specifying a coating that is not able to withstand the exposure environment occurs. However, errors during surface pretreatment and paint application seem to explain many coating damages.[11]

According to ISO 12944-5, corrosivity is an important parameter for coating lifetime.[12] A study of protective coatings on steel bridges in various environments has confirmed this.[13] The effect of corrosivity on coating durability may be caused by the environment chemically attacking the coating, for example, ions penetrating the film, or by the corrosion rate of the substrate under failed coating. A higher corrosion rate will result in faster critical material loss, and coating maintenance will soon be required. It is also well known that insufficient preparation of weld seams, edges and corners, and designs with difficult-to-access surfaces, promote coating deterioration and corrosion.[2,14]

Coating degradation as a function of time can in theory be described by the "bathtub curve," as illustrated in Figure 1. The curve was developed for reliability analysis of electronics,[15] but may also be applied to coatings.[16] According to the curve, corrosion attacks on the coated structure will start to appear shortly after the structure is put in service, due to errors during application of the coating or inherent weaknesses. Then hopefully follows a long period with few but random new corrosion attacks, representing good corrosion protection by a coating that withstands the exposure environment and is applied according to specification. Finally, the

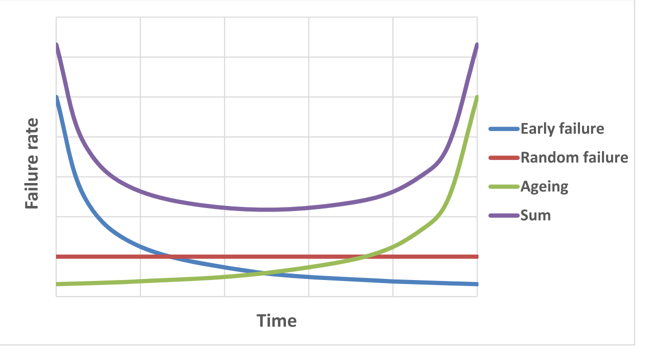

FIGURE 1 The bathtub curve of failure rate as a function of time, applied to failure of a protective coating on a steel structure. [Color figure can be viewed at wileyonlinelibrary.com]

coating starts to fail on a larger scale due to aging and exceeded design life, leading to visible coating failures such as rusting, blistering, flaking, and/or delamination.

The objective with this study was to investigate corrosion attacks on different types of coated structures, to assess the most probable cause of initiation of corrosion, and to identify the most important causes.

2 | MATERIALS AND METHODS

Corrosion attacks on four different coated structures have been investigated with respect to the root cause for the attack. Inspection pictures were made available for the study by the owners of the various structures. The pictures do not cover all corrosion attacks on the structures, but enough pictures have been received to show a representative distribution of the various types of attacks. Table 1 shows information about the structures investigated, the coating systems applied, the age of the coating system at the time of inspection, and number of pictures and corrosion attacks for each structure. The number of pictures and attacks vary between the investigated structures because they vary in size and complexity. The corrosivity category was estimated based on previous experience and measurements on other installations.[13] On "Coastal road bridge 2," corrosivity was measured according to ISO 9226[17] at different locations in the truss work, and the first year corrosion was found to be 12–21 µm, that is, all measurements were within corrosivity category C2.

The coating specification for the offshore oil and gas installation was according to NORSOK M-501, System 1, while the ballast tanks were coated according to NORSOK M-501, System 3B. NORSOK M-501 includes requirements to surface preparation, cleanliness, roughness, and inspection, which were followed.

TABLE 1 Information about the structures investigated in this study, number of inspection pictures, and corrosion attacks.

Type of structure	Estimated corrosivity category	1st coat	2nd coat	3rd coat	Year installed	Coating age at inspection	No. of pictures	No. of attacks
Offshore oil and gas installation, structural steel	Local variation, C3 to CX	75 µm ZnEP	150 µm EPM	60 µm acrylic	After 2010	2–6 years	1062	4600
Ballast water tank	Im4/CX	175 µm EPM	175 µm EPM		After 2010	6 years	203	320
Coastal road bridge 1	C2	75 µm ZnEP	125 µm EPM	75 µm PU	1962	27 years	32	81
Coastal road bridge 2	C2	100 µm TSZ	100 µm Alkyd/CR	100 µm Alkyd/CR	1967	35 years	132	430

Abbreviations: CR, chlorinated rubber; EPM, epoxy mastic; PU, polyurethane; TSZ, thermal spray zinc; ZnEP, zinc epoxy primer.

The two bridges investigated are both suspension bridges with underslung truss work of similar design. Coastal bridge 1 was built in 1962 and originally protected by one or two layers of red lead paint. The paint was probably repaired at regular intervals until 1992, when the entire truss structure was blast cleaned to bare steel and the three-coat paint system with zinc epoxy primer was applied. The second bridge was coated with thermally sprayed zinc and two coats of alkyd/chlroindated rubber paint on top. The coating on this bridge shows sign of spot repair, probably during the 1980s, but no documentation of this can be found.

The root cause of coating failure and initiation of corrosion is suggested from the pictures alone. No testing or measurements have been performed. Typical examples of the corrosion attacks are shown in the results section. The following root causes have been considered:

- *Pretreatment error*: The steel substrate was not properly blast cleaned. This typically results in corrosion rapidly spreading under the paint after initiation.
- *Low dry film thickness (DFT)*: The coating has poor barrier properties, so that corrosion initiates under the paint.
- *Edge retention*: Low DFT over edges.
- *Weld retention*: Low DFT over welds.
- *Overlapping joints*: The bridge truss works were joined by bolting, not welding. Water penetrates the crevice over time and corrosion initiates inside.
- *Mechanical damage*: Objects hitting the surface causing damage to the paint.
- *Galvanic corrosion*: Typically where stainless steel is attached to the painted steel.
- *Cut edge*: Cutting or drilling in the steel after paint application without repairing the coating.
- *Cracking*: The coating is cracking. No evaluation of what caused the cracking.
- *Pinholes*: Small holes in the coating formed during application, usually caused by outgassing or solvent evaporation.
- *Chemical degradation*: The coating is chemically attacked by the environment.

Other failure mechanisms have also been found, for example, flaking due to poor intercoat adhesion, but the number of such failures was below 1% on all the investigated structures and were therefore disregarded in this investigation.

3 | RESULTS

In this section, pictures representative of the most important types of corrosion attacks are shown, along with a percentage distribution among the various types of attacks for each installation.

3.1 | Topside offshore oil and gas installation

The investigation was limited to structural steel. Process equipment like pipes, valves, tanks, and so on were not included since various coating systems are applied and the exposure conditions vary more (e.g., operational/process temperatures were unknown to us). The coating was specified and prequalified according to NORSOK M-501 System 1.

Several corrosion attacks can be seen on the steel structure in Figure 2. The picture shows a support structure for process equipment made from rectangular

FIGURE 2 Corrosion attacks on painted steel structure. Attacks typically initiate at welds and edges, but in this picture we also see attacks on flat surfaces, indicating that the film thickness is below specification. [Color figure can be viewed at wileyonlinelibrary.com]

hollow section (RHS) steel beams. Corrosion has initiated at the edges of the RHS beams and in the weld joints. Corrosion attacks have also initiated on flat surfaces, indicating that the film thickness of the paint is below specification. The RHS beams are produced with a longitudinal weld on one side, and corrosion has also initiated at this weld. Low film thickness in general has probably contributed to the coating failures over edges and welds as well. RHS profiles are also delivered with a specified outer edge radius, typically in the range 5–30 mm depending on their dimensions. The beams in the picture have an edge radius of at least 10 mm, which should decrease the edge retention problem significantly.

Figure 3 shows various corrosion attacks with different root causes. Figure 3a shows initiations mainly along edges, but also emerging corrosion on welds in the inner corner. Figure 3b shows galvanic corrosion around stainless steel profiles. The stainless steel profiles should

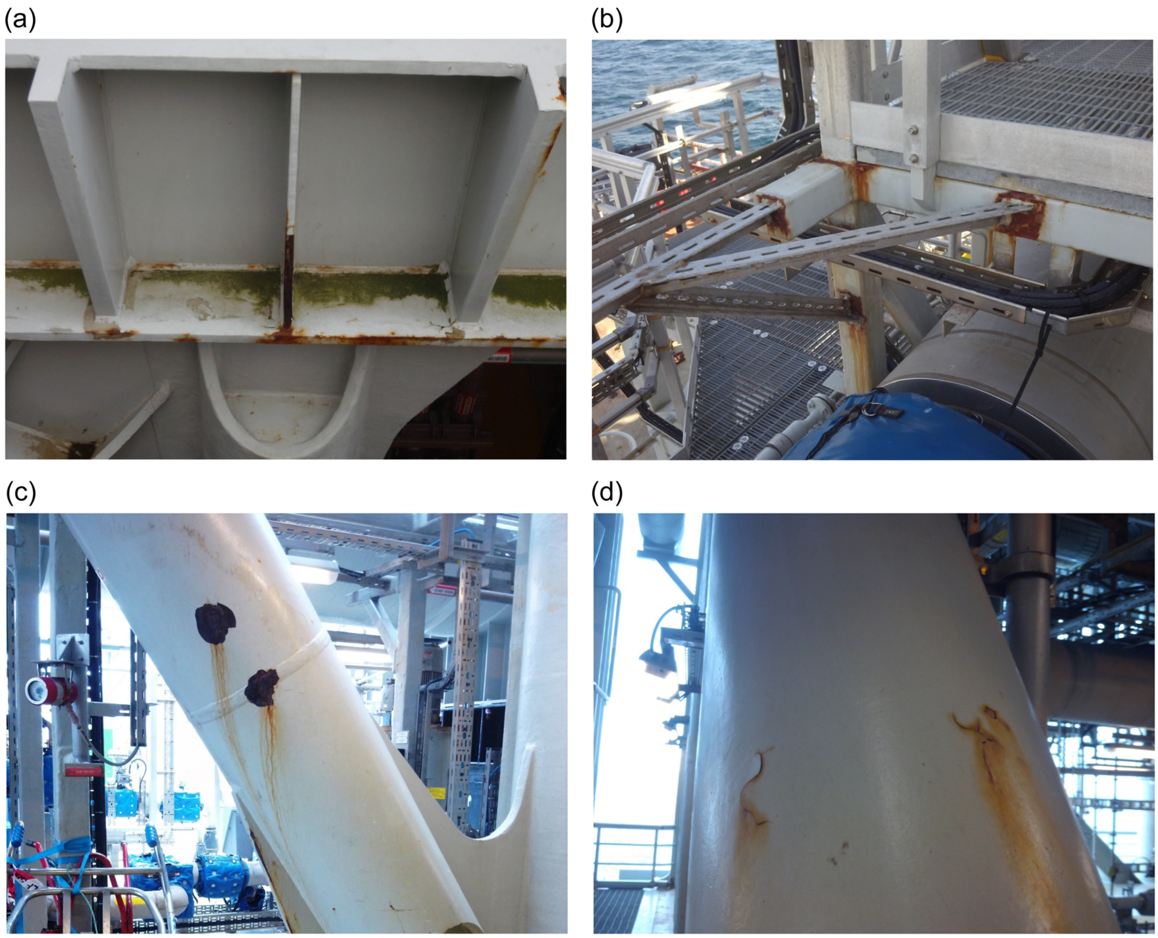

FIGURE 3 Corrosion attacks on painted steel on offshore installation with different root causes. (a) Corrosion attacks initiating from edges; (b) galvanic corrosion around stainless steel welded into the structure; (c) poor pretreatment before paint application; (d) the paint is cracking and corrosion initiates in the cracks. [Color figure can be viewed at wileyonlinelibrary.com]

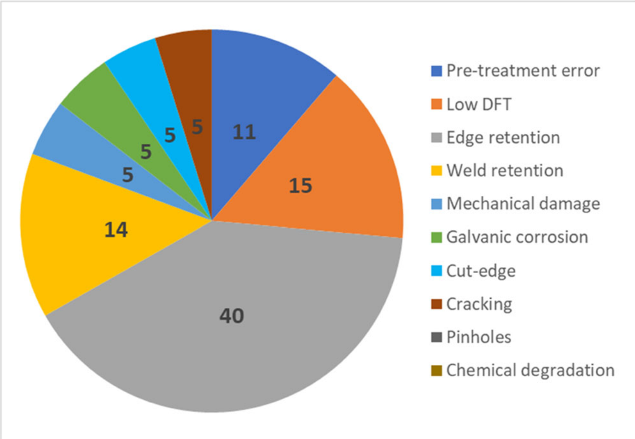

FIGURE 4 Percentage distribution of root cause for corrosion on painted steel on topside oil and gas offshore installation. [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 5 Typical corrosion attacks in ballast water tank after 6 years in service. [Color figure can be viewed at wileyonlinelibrary.com]

have been painted 50 mm beyond the weld to minimize the cathodic surface area, but this has not been done, resulting in widespread corrosion around the weld. Figure 3c shows corrosion rapidly spreading under the paint due to poor surface pretreatment. The corrosion products strain the paint film and cause the paint to break off in pieces. Figure 3d shows cracking of the paint, and subsequent corrosion in the cracks. To explain what caused the cracking is beyond the scope of this work, but internal stresses seem likely, since no signs of mechanical damage can be seen.

The percentage distribution of failure mechanisms for all the corrosion attacks are shown in Figure 4. Pretreatment errors and low DFT (application errors) explains about 25% of the corrosion attacks, while edge and weld retention caused about 55% of the attacks. Edge and weld retention failures are caused by the same mechanisms. After application, the wet paint will try to reduce its surface area on the structure due to its surface tension. The paint will therefore be thinner over any protrusion or irregularity in the substrate, like edges and welds. The final dry film will therefore be thin and have inferior barrier properties, allowing ions to penetrate and initiate corrosion.[16] The remaining corrosion attacks were caused by mechanical damages, galvanic corrosion, cut-edges, and cracking. Pinholes and chemical coating degradation were not found on this installation.

3.2 | Ballast water tank system

The coating was specified and prequalified according to NORSOK M-501 System 3B. The ballast water tanks were attacked by corrosion mainly on edges, as shown in Figure 5.

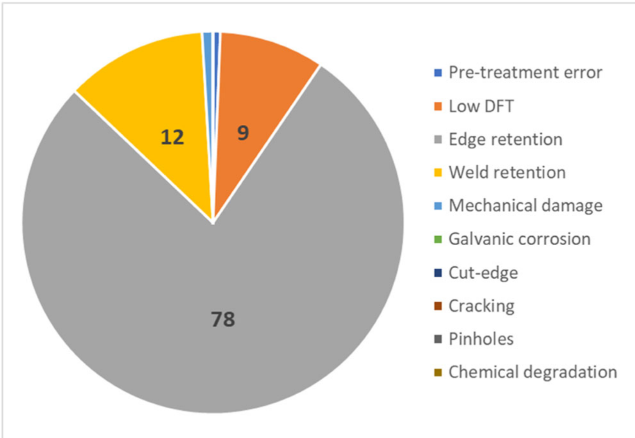

FIGURE 6 Percentage distribution of root cause for corrosion on painted steel in ballast water tanks. [Color figure can be viewed at wileyonlinelibrary.com]

Some attacks were also found on welds, and some attacks were attributed to low film thickness. Figure 5 shows several smaller areas with a brighter shade of gray, indicating that touch-up repairs were performed in the yard. No coating repair has been done after the ballast tanks were taken in use. Figure 6 shows the percentage distribution of corrosion attacks. Edge retention errors accounted for 78% of the coating failures, while weld retention and low film thickness explained the remaining attacks.

3.3 | Coastal road bridge truss structure with three-coat paint system

The coating system on this bridge was similar to the system on the offshore installation, see Table 1. Figure 7 shows a

FIGURE 7 Typical corrosion attacks on bolted truss work on a coastal steel bridge protected with a three-coat paint system. [Color figure can be viewed at wileyonlinelibrary.com]

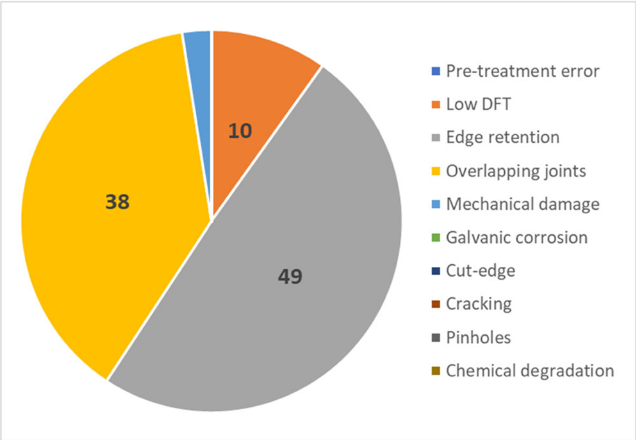

FIGURE 8 Percentage distribution of root cause for corrosion on painted steel on bolted thruss work on a coastal steel bridge protected with a three-coat paint system. [Color figure can be viewed at wileyonlinelibrary.com]

connection at the upper chord of the truss work that illustrates the corrosion attacks on this bridge well. Several corrosion attacks have initiated from edges on the members and the plates in the connection. Since this bridge was not welded but bolted, many of the corrosion attacks initiated from the overlapping bolt joints. The paint has not penetrated the crevices in the many lap joints, resulting in corrosion as shown in the picture. The crevice between the concrete bridge deck and the beam it is resting on, is also an area with many initiation points for corrosion.

Figure 8 shows the percentage distribution of corrosion attacks estimated from the inspection pictures of the bridge. Edge retention (49%) and poor penetration into overlapping joints (38%) explains most of the corrosion attacks on the bridge. Low DFT and

FIGURE 9 Typical corrosion attacks on bolted thruss work on a coastal steel bridge protected with a TSZ duplex coating system. [Color figure can be viewed at wileyonlinelibrary.com]

mechanical damages caused 10% and 2% of the damages, respectively.

3.4 | Coastal road bridge truss structure with thermal spray zinc (TSZ) duplex coating

The truss structure of this bridge has an identical design to the bridge discussed above, but the steel was protected with a TSZ duplex coating system from the start. Figure 9 shows a connection in the truss work, identical to the one shown in Figure 7 for the other bridge. Comparing the two pictures, we see that the two coating systems have quite different weaknesses that result in corrosion. There is less corrosion initiating from edges, and corrosion from the lap joint crevices is almost completely absent.

Corrosion due to low DFT is still present. Low DFT of the paint is difficult to detect in a TSZ dupex coating, which may have contributed to this.[18] The thickness gauge used for controlling film thickness is based on magnetism, that is, it measures thickness down to the first magnetic material, which will be the steel. Both zinc and paint will then be measured, and too high film thickness of the zinc will prevent detection of low DFT in the paint. Thickness gauges may also use eddy current, that is, measure thickness down to the first electrically conducting material, that is, the zinc. However, the TSZ has so rough and inhomogeneous structure that electric conductivity varies too much for reliable thickness measurement by this principle.[13]

Degradation from pinholes in the coating, however, is more common on TSZ duplex coatings. During application of paint on TSZ, the phenomenon of popping is a commonly encountered problem, resulting in pinholes in the paint film. Due to the rough structure of the TSZ, solvent evaporation easily results in formation of gas

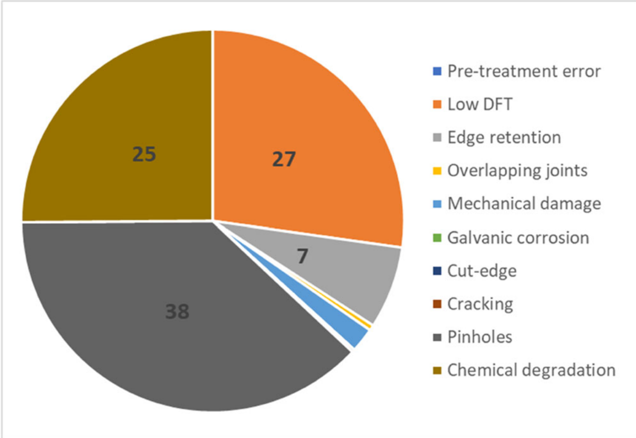

FIGURE 10 Percentage distribution of root cause for corrosion on painted steel on bolted thruss work on a coastal steel bridge protected with a thermal spray zinc duplex coating system. [Color figure can be viewed at wileyonlinelibrary.com]

bubbles in the wet film.[18] These bubbles may crack at a stage when the film is too viscous to close the hole, and subsequent paint layers may not fill all the holes. The TSZ is exposed to the environment in these pinholes and starts to corrode at an early stage. The white spots in the paint on the beam under the concrete deck are most likely zinc corrosion products from such pinholes.

The paint system on this bridge is partly based on an alkyd binder. In contact with the concrete, the alkyd is susceptible to hydrolysis due to the alkaline pore water from the concrete. Hence, chemical degradation of the coating is often found near the concrete, with subsequent corrosion of the zinc and eventually the steel.

Figure 10 shows the distribution of root cause for corrosion on the TSZ duplex coated bridge. Low DFT, pinholes, and chemical degradation of the paint explain most of the attacks.

4 | DISCUSSION

4.1 | Coating failure mechanisms

This study shows that the coating failure mechanisms found on a structure depends on both the type of structure and the type of coating that is applied. If several structures of the same type had been investigated, we would have found variations between them also, but that is beyond the scope of this work. However, some types of failures were recurring on all the structures. In sum, edge and weld retention was the main cause of corrosion on painted steel for the investigated structures. This is a well-known problem and has been reported before,[2,14] and ISO 8501-3 describes how the problem shall be reduced by rounding edges by grinding.[19] Weld caps cannot be grided flat, since they in many cases contribute to the weld strength. Corrosion due to low DFT was also found on all the structures, while the other failure mechanisms were more dependent on structure or coating type.

On the topside oil and gas installation, many different failure mechanisms were found, while on the other structures a few types of failure dominated. This can be explained by the size and complexity of the structure, but also that this is a workplace and therefore susceptible to mechanical damages. Another factor that has affected coating performance on offshore oil and gas installations in general is the urgency to complete the construction on time to start production according to plan. Coating application is among the tasks that are performed towards the end of the construction period, and to meet deadlines, the structure can be installed offshore before all painting has been completed. The remaining paint work can be completed offshore. Urgency to complete the paint application and any restrictions on blast cleaning may result in poor pretreatment, lack of inspection and other quality reducing shortcuts to save time. However, specifying coatings according to NORSOK M-501 includes requirements to surface preparation, cleaning, application, and inspection. When followed, these requirements will improve the performance of the coating.

The ballast water tanks showed signs of local coating repairs, which must have been done in the yard since no maintenance operations had been performed after the structure was taken into use. Few corrosion attacks were associated with low film thickness, which then probably can be explained by careful control and inspection of the coating during application. The coating generally appeared to be in good condition, with few and small corrosion attacks.

The steel bridge protected with a three-coat paint system was mainly attacked by corrosion at edges and overlapping joints. The many corrosion attacks on edges reflect the problem with edge and weld retention also found on the topside oil and gas installation and the ballast water tanks. Corrosion at overlapping joints, however, is largely eliminated in newer structures by welding. The modern box girder bridge design also reduces the amount of edges in the steel structure, which also will be beneficial with respect to coating performance.[20] The other bridge protected with a TSZ duplex coating system, however, showed a very different distribution of coating failure mechanisms. The TSZ seems to have closed all the overlapping joints and very few initiations were found at such joints. Also, a few corrosion attacks originating from edges were found. Since the TSZ solidifies immediately when it hits the steel substrate, the film thickness over edges will be nearly the same as on flat surfaces. This may increase the radius of edges, reducing the edge retention problem of subsequent paint layers. The TSZ has significant degradation from pinholes though, and this seems to be rather specific to this type of coating. The hydrolysis of alkyds in contact with concrete is a well-known problem,[21] and the general transition from alkyds to epoxies in protective coatings will eliminate this problem, since epoxies are very tolerant to alkali.

4.2 | Coating lifetime

This investigation has shown that most of the coating failures were related to problems in the application of the paint, either edge and weld retention, low DFT, poor surface pretreatment, or pinholes. Hence, the quality of the workmanship will to a large extent determine the coating performance. However, edge and weld retention are inherent properties of liquid paint. Edges are supposed to be rounded before paint application, but this is both costly and difficult to get right.[16] It is therefore important to also consider application properties and physical and mechanical properties (e.g., edge covering properties) when specifying coating systems.

Given the large fraction of corrosion attacks caused by defects in the coating from the application, the structures most likely started to corrode shortly after they were exposed to the environment. According to the bathtub curve, the lifetime of the coatings is determined by early failure. Since corrosion in most cases is a slow process, these corrosion attacks will be acceptable for a long time, until the attacks have developed to a stage where they are regarded as a threat to integrity or function of the substrate. Depending on the corrosivity, this period may be very long. The truss work on the two coastal bridges investigated were located high above the sea in corrosivity class C2. Almost all the corrosion attacks were shallow and not a threat to the load baring capacity of the structure (Figure 7). The coatings have therefore not been repaired during their more than 30 year lifetime. Large parts of the topside oil and gas platform, on the other hand, is exposed in a very corrosive environment, and the corrosion attacks will become critical to repair much earlier. This at least partly explains the correlation between corrosivity and coating lifetime.[13]

Careful control during the paint application and good workmanship will of course improve coating performance and increase lifetime, as demonstrated by the the ballast water tanks that we believe were well inspected during and after application. Fewer corrosion attacks were found, and therefore the probability of corrosion in critical areas is lower.

4.3 | What triggers coating maintenance?

Many of the corrosion attacks found in this investigation are not critical with respect to integrity of the structure, see for example, Figures 2, 5, 7, and 9. Many structures have requirements to visual appearance that may trigger coating maintenance, but the attacks seen in the figures do not require maintenance for securing structural integrity. For an oil and gas installation, risk assessment is usually key for prioritizing coating maintenance, that is, risk-based maintenance.[22] If failure of an item has severe consequences, the chance of failure must be kept low to keep the risk at an acceptable level. Hence, coating maintenance must start at an earlier stage. Even so, the aesthetical function of the coating influences both perceived safety and attention to safety barriers,[22] that is, there are arguments for starting coating maintenance earlier than the risk assessment advises. Availability of resources, like personnel or funding, may also dictate when coating maintenance should start. Lately, the industry has started treating the coating as a maintenance object in its own right, and not just a safety barrier against corrosion of the substrate. This will also affect priorities with respect to maintenance. In general, life cycle cost will be secondary to risk with respect to prioritizing maintenance.

The Norwegian Public Roads Administration, owner of the two bridges included in this study, has a life cycle cost strategy with respect to coating maintenance. In practice, they have concluded to repair coatings at an early stage of the degradation to reduce the amount of blast cleaning, which is expected to reduce the costs of each maintenance operation. Both bridges in this study had coating maintenance performed in 2022. On the bridge with the three-coat paint system, most of the corrosion attacks were not critical, as shown in Figure 7. However, in some locations, corrosion products in the overlapping joints were breaking the joint apart, see Figure 11. This will eventually become a threat to load-bearing capacity and must be stopped. Since scaffolding was required under the entire bridge, total refurbishment of the coating was decided as a preventive measure. The additional cost was assumed to be a good investment, since the time to next maintenance operation would be significantly extended. The bridge with the duplex coating had no critical corrosion attacks, but the coating was repaired because the bridge needed strengthening of the trusswork. Since the scaffolding had to be installed for the

FIGURE 11 Corrosion products breaking the overlapping joint apart. [Color figure can be viewed at wileyonlinelibrary.com]

mechanical work, the additional cost for coating maintenance was justified by extended time to next maintenance.

The above examples show that the criteria for starting coating maintenance depend on company-specific priorities, type of installation, and circumstances.

4.4 | Coating selection

Coating selection standards, for example, ISO 12944-5[12] and NORSOK M-501[9] rely to a large extent on scribe creep corrosion testing for prequalification of coating systems. This investigation has shown that corrosion creep from the damage was slow in most cases, see for example, Figures 3c and 5, even in such very corrosive environments. A previous study of correlation between accelerated scribe creep corrosion tests and a field test showed that high-quality epoxy-based protective coatings indeed have a high resistance to corrosion creep.[23] Other studies, including less resistant coating systems, have shown a certain correlation between accelerated tests and field tests.[6] Hence, accelerated testing has been found to distinguish between high- and low-quality coating systems, but the strong focus on corrosion creep in prequalification testing seem unjustified from this work.

5 | CONCLUSIONS

Errors from the application of the coating were the dominating factor for coating failure and corrosion on painted steel structures.

Poor edge and weld retention was the most frequently found failure mechanism for the three-coat paint systems investigated. The TSZ duplex coating was quite resilient to this type of failure but was more susceptible to pinholes.

Corrosion creep around the coating damage was limited, even in very corrosive environments, if surface pretreatment was according to specification. The strong focus on this property in prequalification testing therefore seems exaggerated.

When a coated structure is put in service with many errors and weaknesses in the coating, the structure will start to corrode after a short time. Time to first major coating maintenance operation, that is, coating lifetime, will then depend on the corrosion rate of the exposed steel. In a high-corrosivity environment, the material loss will soon reach a critical level. In a low-corrosivity environment, coating maintenance can be postponed for a long time before the corrosion becomes a threat to integrity of the structure.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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