

Examination of Uncertainties in the Corrosion-Fatigue Design and Assessment of Offshore Wind Support Structures

A dissertation submitted by

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Abstract:

Offshore wind support structures are subjected to very harsh marine conditions over the course of their approximately thirty-year design life. These conditions combine a high number of load cycles with a corrosive environment that makes the combined effect of corrosion-fatigue an important design variable. Corrosion-fatigue damage is a highly interdisciplinary topic that bridges gaps among different information silos in the offshore wind space. This dissertation work is divided into three sections that address specific gaps in among the different domains required to understand corrosion-fatigue for offshore wind. Some gaps lie within specific disciplines such as fatigue assessment where there are broadly defined “fatigue demand” and “fatigue capacity” halves. To address this gap, a critical analysis of the available corrosion-fatigue test data was combined with a fatigue assessment of a real offshore wind support structure. This was done to measure the sensitivity of fatigue damage results to capacity assumptions and to highlight what forms of new corrosion-fatigue testing might be needed to support offshore wind. Another gap lies between corrosion protection engineering and structural engineering. Here, an evaluation of the uncertainties associated with cathodic protection systems based on experience in Europe, provides insight into the needs for more precise corrosion-fatigue damage models. Finally, there were gaps between the engineering work designing these structures and the policy and environmental work focused on how OW fits into the larger blue economy and environmental conservation. This space was filled by creating a new framework called nature inclusive offshore wind farms (NIOWFs) to identify the engineering questions most pertinent for a sustainable and equitable offshore wind industry.

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Chapter 1 Introduction to Dissertation

Offshore wind energy represents a critical component of the global transition to renewable energy, with steady deployment across Europe and a nascent market in the United States. As offshore wind turbines have gotten larger and are deployed in deeper waters, the long-term durability of structural details in the support structures is an increasingly important design consideration. This dissertation examines the interrelated challenges of corrosion, fatigue, and environmental impact in offshore wind support structures, with a focus on monopiles. Corrosion and fatigue damages combine into the process of corrosion-fatigue. Corrosion-fatigue is the combined degradation mechanism where cyclic loading interacts with corrosion processes, in a way where the total of the two damage processes is greater than the sum of their separate parts. These structures are designed to withstand millions of load cycles in harsh marine environments over 25 or more years, with limited opportunities for inspection and maintenance.

This research draws heavily on European experience, where offshore wind has matured over three decades, and emerging data from U.S. installations. The primary goal and novelty of the dissertation is the identifying research gaps at the intersections of information silos within the offshore wind industry. This includes structural designers focused on fatigue, corrosion engineers focused on corrosion protection systems, and environmental experts focused on minimizing environmental impact. The dissertation addresses three interconnected research questions:

- 1.) What is the history of corrosion issues on offshore wind monopiles in Europe? What lessons can be learned to avoid similar issues in U.S. installations? What areas of the monopile are most likely to have corrosion risk?

- 2.) What are the limitations to our current ability to model corrosion-fatigue damage? What damage models are most popular? How do the limitations in available test data affect our understanding of corrosion-fatigue risk for offshore wind structures?
- 3.) How do the interactions between corrosion-fatigue damage, corrosion risk, and real data from an offshore wind turbine support structure combine to affect estimated remaining useful life? What consequences are there for how we measure fatigue damage and how could they inform future corrosion-fatigue testing for offshore wind?
- 4.) What features are of most interest on an offshore wind monopile from a corrosion-fatigue standpoint? Where are the research gaps for future study?
- 5.) How does this discussion around corrosion protection, fatigue, and design life extend into other areas important for ocean stakeholders and the blue economy as a whole?

Chapter Overview

Chapter 1 presents an initial overview of the document, and the key themes addressed therein. It also provides the breakdown of the chapter structure as a guide for the reader. Next Chapter 2 introduces the technical definitions and concepts addressed in this dissertation. These chapters introduce the document and provide context for the following chapters describing the primary contributions of my PhD research.

Chapter 3

Chapter 3 focuses specifically on the challenges of internal corrosion within offshore wind monopiles. Drawing from European experience and lessons learned over the past two decades, this chapter traces the evolution of internal corrosion protection systems from early monopile designs through current practice. The chapter analyzes the interdisciplinary nature of internal corrosion control,

exploring the complex interplay between water chemistry, coating performance, and microbiologically influenced corrosion.

Primary Contributions of PhD Research

The history of corrosion issues inside of monopiles had not been previously compiled beyond conference papers on individual topics. Requirements from design documents and industry insights were analyzed to understand the interaction of corrosion protection methods, fatigue design, and holistic foundation design. Based on this, new insights were made into how to design suitably robust internal corrosion protection systems.

Chapter 4

Chapter 4 presents a detailed analysis of corrosion-fatigue capacity testing, examining how environmental conditions interact with loading variables to affect fatigue performance. The chapter includes data from linear elastic fracture mechanics testing as well as SN curve testing. A particular focus is given to finding where there are limitations in the available data and how it may affect the use of SN curves for damage calculations.

Primary Contributions of PhD Research

Key limitations in corrosion-fatigue research are identified. A deep review of the early 1980s testing was done to establish the environmental reduction factors of the original SN curves and this shows that there is significant variability in important metadata such as frequency and temperature. There is also variability in the ERF results themselves. These findings support work done by Dr. Wangwen Zhao who concluded that there was not enough cathodic protection and free corrosion data on butt welds to build an uncertainty model. The limitations about how constant amplitude SN curve testing

only supports the curve up to $1E7$ cycles are further explored in the next chapter when fatigue demand from a monitored offshore wind turbine is introduced.

Chapter 5

Chapter 5 bridges laboratory testing and field observations through an analysis of fatigue demands and capacity in operational offshore wind structures. Using data from the Block Island Wind Farm (BIWF), this chapter demonstrates how capacity assumptions significantly impact fatigue damage estimation and remaining useful life calculations, highlighting the importance of accurate stress concentration factor assessment and appropriate SN curve selection.

Primary Contributions of PhD Research

Chapter 5 connects fatigue demands from an offshore wind structure with the SN curves discussed in Chapter 4. While there is much SHM research about the fatigue demands of offshore wind turbine support structures, much of this work uses the damage equivalent load/stress metric. This simplified metric only accounts for the assumed slope of the SN curve and does not capture the true behaviour of fatigue testing that we see in the SN data. The fatigue demand data from an offshore wind jacket is used to answer critical questions such as:

- What are the consequences of using the equivalent stress simplification?
- What section of the SN curve is driving the damage and what testing should be done to fill the gap?
- How sensitive is the relationship between measured fatigue damage and environmental conditions to capacity assumptions such as the SCF?

Chapter 6

Chapter 6 synthesizes findings from previous chapters, providing an integrated perspective on corrosion-fatigue in offshore wind foundations. This chapter identifies critical research gaps and offers practical recommendations for design, inspection, and monitoring of offshore wind monopiles.

Primary Contributions of PhD Research

Chapter 6 provides a generalized framework/guide for fatigue analysis that was developed after practicing fatigue damage calculations on multiple different structures. The gaps between the way fatigue demands are calculated by modelers and digital twin builders versus how fatigue testing is done, and SN curves are calculated, are displayed to emphasize the need for new testing combining pre-corroded specimens and variable amplitude loading. No other groups have examined how the stress histograms interact with the bilinear SN curves.

Chapter 7

Chapter 7 explores the concept of nature-inclusive offshore wind farms, examining how European experience in nature-inclusive design can be applied to developments along the U.S. East Coast. This chapter broadens the dissertation's scope to consider how offshore wind foundations can potentially serve ecological functions while generating clean energy while also contributing to a sustainable blue economy that balances energy production, economic development, and environmental stewardship.

Primary Contributions of PhD Research

This work was inspired by a proposal that went to NSF for MOCEAN. The goal of that proposal was to build an organization that focused on three pillars: energy production, environment stewardship, and economic development. Efforts in Europe have focused on combining offshore wind energy and

environmental stewardship under the NID umbrella, but the economic development lens had not historically been well incorporated. This work adds in the economic development lens to NID under the new umbrella term, nature inclusive offshore wind farms NIOWFs. This NIOWF framework was then applied to Europe where it was found that there were three main approaches: policy (MSP), marine biology (NID), and economic development/commercialization (multi-use). In the NID framework these three fields are all interconnected and critical for NIOWFs. This same breakdown of MSP, NID, and NIOWFs was applied to the US to identify key stakeholders and organizations that would need to coordinate to apply the NIOWF framework to the US market. After sketching out the US market and comparing it to Europe, key barriers to US NIOWFs were discussed in the last section. This positive vision for the ocean in the US OW market has not been clearly established and backed up by research work in Europe previously in the literature.

Chapter 2 Introduction to Corrosion and Fatigue Concepts

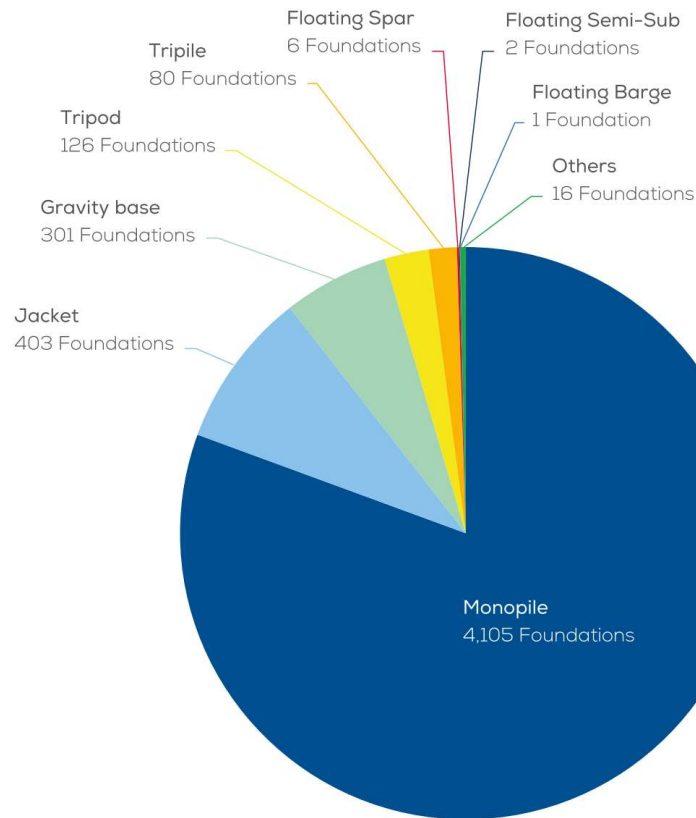
The work in this dissertation began in 2019 with a review of corrosion and fatigue issues from the first round of European offshore wind farms. The European offshore wind market is far more mature than the offshore wind market in the United States. The first European offshore shore wind farm was built in 1991 in Vindeby Denmark with 11 turbines to produce 24.95 MW (Jensen et al., 2018). In 2019 the market in Europe had grown to 3,589 turbines producing 12,631 MW and today in 2025 the total installed offshore wind capacity in Europe is 37 GW (Komusanac et al., 2021; Musial et al., 2023; Wind Europe, 2018a). Although much of the data on the long-term fatigue performance of these existing offshore structures is proprietary, the US market can still learn from the limited amount of information in the public domain.

This section is derived from the original report on corrosion-fatigue issues and is broken into four sections. First, offshore wind monopiles are defined, and a brief history of their issues with corrosion and fatigue is reviewed. Second, corrosion and corrosion protection are defined and described. Third, fatigue damage and models are defined and the relationship between fatigue and corrosion is described in the form of corrosion-fatigue.

2.1 Description of European Monopiles

First key context about the European market is needed. As of 2018 Monopiles made up 80% of the installed offshore foundations for wind turbines in Europe as of 2018, see

Figure 1. Other foundation platforms, such as jackets and gravity-based foundations, have also been used for offshore wind but these foundations are not nearly as common as monopiles (Wind Europe, 2018b). As a result, much of the European research and focus is on the long-term performance of monopiles.



Source: WindEurope

Figure 1 Foundation types used in Europe (From Wind Europe annual report, 2018, Figure 17)

Monopile foundations are installed by driving a large diameter pile into the seabed. Often a transition piece (TP) is then installed on top of the monopile, but modern wind farms have begun introducing TP-less designs. Next, the wind turbine tower is attached to the support structure. An example from the Coastal Virginia Offshore Wind (CVOW) Pilot project can be seen in Figure 2.



Figure 2 CVOW Offshore Wind Pilot (Image from CVOW)

Figure 3 shows the development of the connections used to join the transition piece to the monopile (van Gelder, 2019). From approximately 2006 to 2008 the most common connection was grout with no shear keys. This grouted connection was revealed to be inadequate in 2009 when the transition pieces were found to be sliding down the piles at some wind farms (Jensen et al., 2018). These grouted connections failed due to fatigue damage and a joint industry project was done to determine the capacity of grouted connections with shear keys (Lotsberg, 2013). In addition to the grouted connections with shear keys, grouted cone and bolted flange connections have been used to connect the transition piece to the monopile. In the modern era of monopile design most support structures use a bolted flange connection.

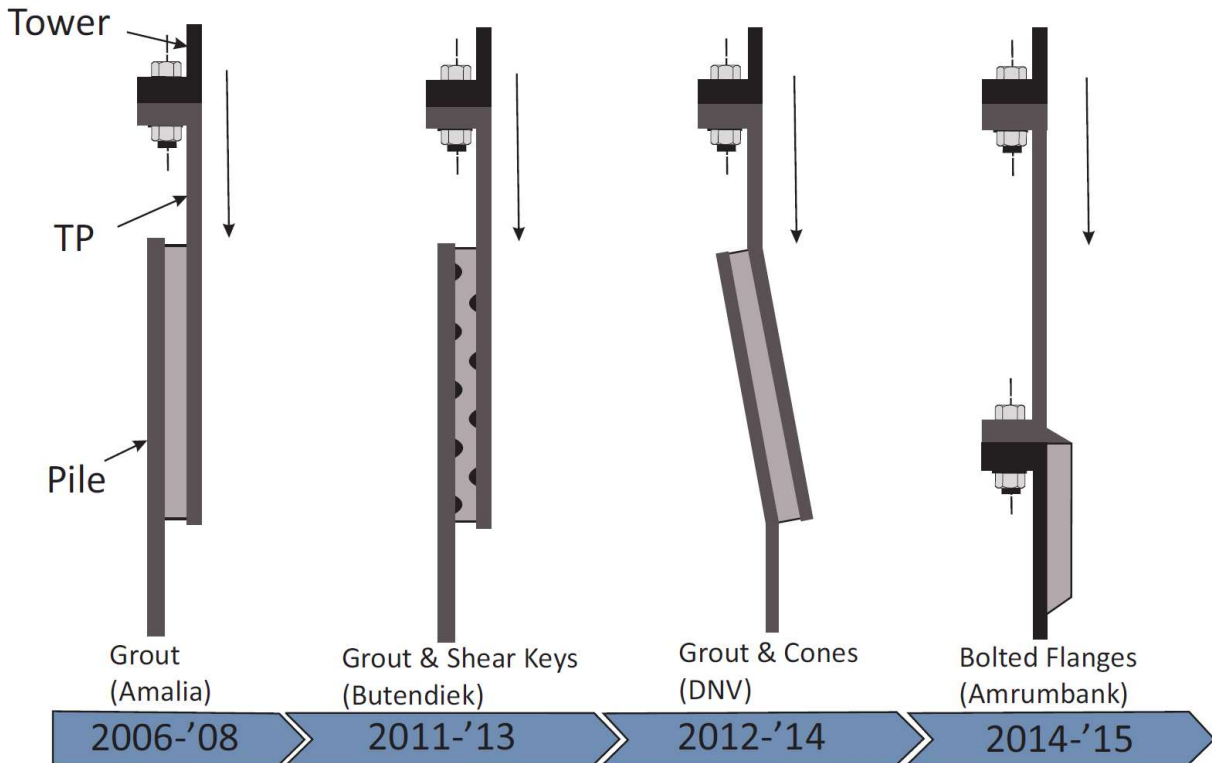


Figure 3 Monopile transition piece connection designs (redrawn from van Gelder Presentation)

These developments in monopile design present a challenge. The most valuable information is about the long-term fatigue performance of these structures. However, much of the research and information in Europe is focused on retrofitting and monitoring the original monopiles built between 2002 and 2009 with grouted connections without shear keys. Modern monopiles with new connection designs and practices do not have the same track record. From 2016-2022 several updates to standards were made because of observations made about these first generation monopiles and this is discussed more in Chapter 3.

2.1.1 Monopile Interiors

Failure of the grouted connection between the pile and the transition piece caused the TP to settle and led to unexpected seawater and oxygen exchange between the interior and exterior of the

monopile. This situation was studied extensively by a group that published conference papers at NACE and EuroCorr (Black, Mathiesen, & Hilbert, 2015). The designs for these early monopiles assumed that the corrosion rate inside of the monopiles would be very slow because it would be a low-oxygen environment with no exchange between the inside and outside. This meant the monopiles were designed without any internal corrosion protection. When this assumption was incorrect, the higher-than-expected corrosion rates meant that the fatigue life needed to be reevaluated to account for free corrosion conditions. A photo taken from the inside of a monopile with insufficient corrosion protection is presented in Figure 4 to show the extent of the corrosion issue (Lichtenstein, 2015). More details on the specifics of internal corrosion issues can be found in Chapter 3 as an example of how corrosion protection has been a challenge for the offshore wind industry.



Figure 4 Image of monopile interior without proper corrosion protection (from Lichtenstein 2015)

2.1.2 Fatigue Demand and Monopiles

Wind turbines are highly dynamic structures. As one industry member joked during a discussion about corrosion fatigue: “A wind turbine is designed to do two things. 1.) Generate Power. 2.) Destroy its

foundation”. For offshore wind turbines dynamics are even more important because the support structure must be built to handle both wind and wave loads.

Figure 5 from the IEA 15 MW reference wind turbine document shows the frequency content of loads on an offshore wind turbine including the wind spectrum, 1P loads, 3P loads, and wave loads (Gaertner et al., 2020). The wind spectrum and wave spectrum are self-explanatory while 1P is the frequency of a single rotation of the turbine, and 3P is the frequency at which blades pass in front of the tower (Arany et al., 2017). The figure also shows how the natural frequency of the tower is designed to avoid the 1P and 3P frequencies as well as the typical frequency of the wave loads.

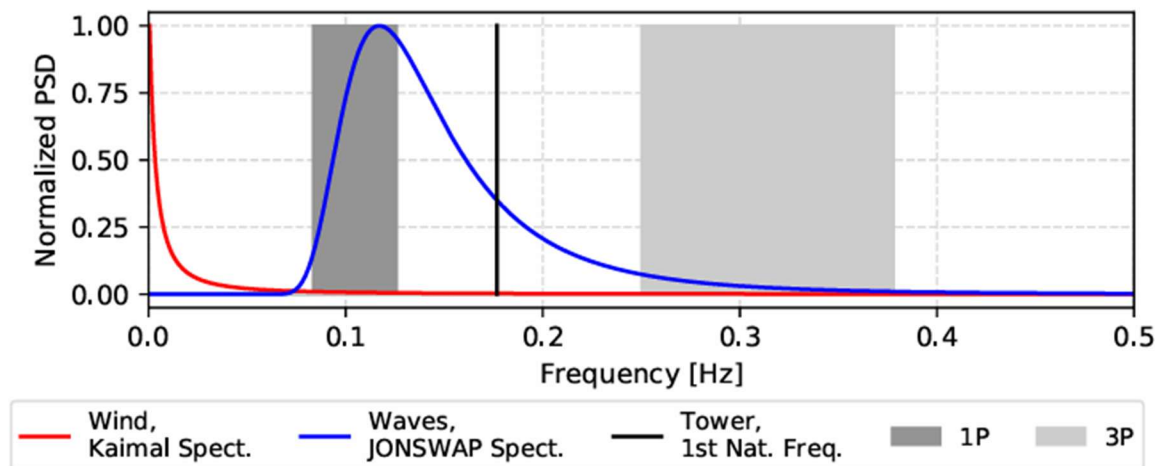


Figure 5 Frequency Target Diagram (from IEA 15 MW)

2.1.3 Fundamentals of Corrosion

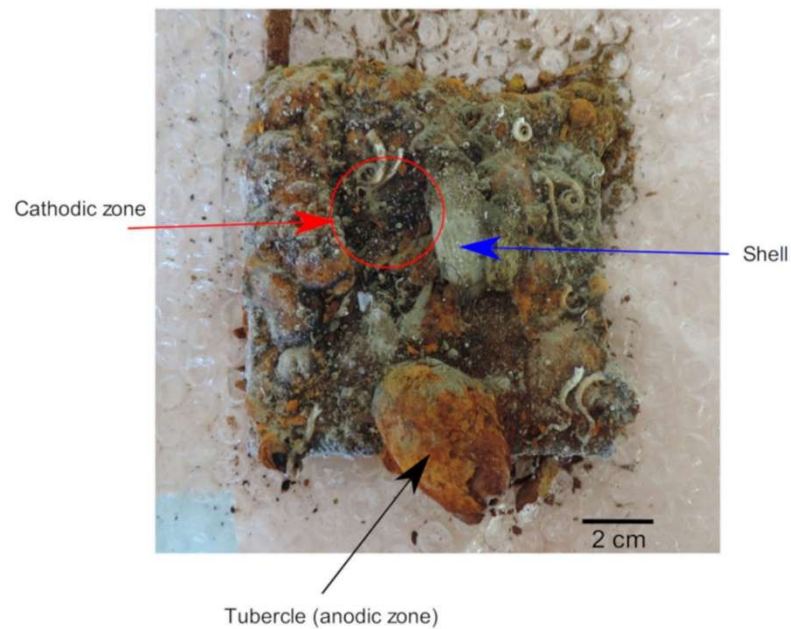


Figure 6 Example of Real Corrosion Coupon (Source: Refait 2020)

Corrosion damage occurs due to the flow of electrons from an anode to a cathode. In a typical corrosion reaction, iron Fe^0 turns into an iron ion Fe^{2+} at the anode. The conversion of Fe^0 to Fe^{2+} causes material loss at the anode. Figure 6 shows an example of real corrosion from a laboratory test (Refait, Grolleau, Jeannin, Rémazeilles, & Sabot, 2020). In Figure 6, a tubercle has formed over the anode. The tubercle is a bubble of corrosion products, which hides the loss of material at the anode. The cathode can be also be identified in Figure 6 because the color of the chemical products is black as opposed to the red-orange color of the anode (Refait et al., 2020).

2.2 Fundamentals of Corrosion Protection

Offshore wind farms are often built with a 25-to-30-year lifespan and unlike oil and gas platforms they are unmanned. This means that any corrosion protection system needs to have minimal maintenance and human intervention requirements over the life of the structure. There are three

general ways a designer can prevent and account for corrosion coatings, cathodic protection, and corrosion allowances. Different corrosion control techniques are used at different parts of the structure.

Figure 7 breaks up a monopile into the corrosion zones used in DNVGL-RP-0416 (DNV GL, 2016a). These DNV GL definitions are good baseline because they are the most developed and are commonly used. The following zones are found across other design documents:

1. Atmospheric Zone: The region exposed to the atmosphere above the splash zone.
2. Splash Zone: The region that is wetted from tidal variation and wave action.
3. Submerged Zone: The region below the splash zone that is immersed in seawater.
4. Buried Zone: The zone below the mudline that is buried in the seabed.

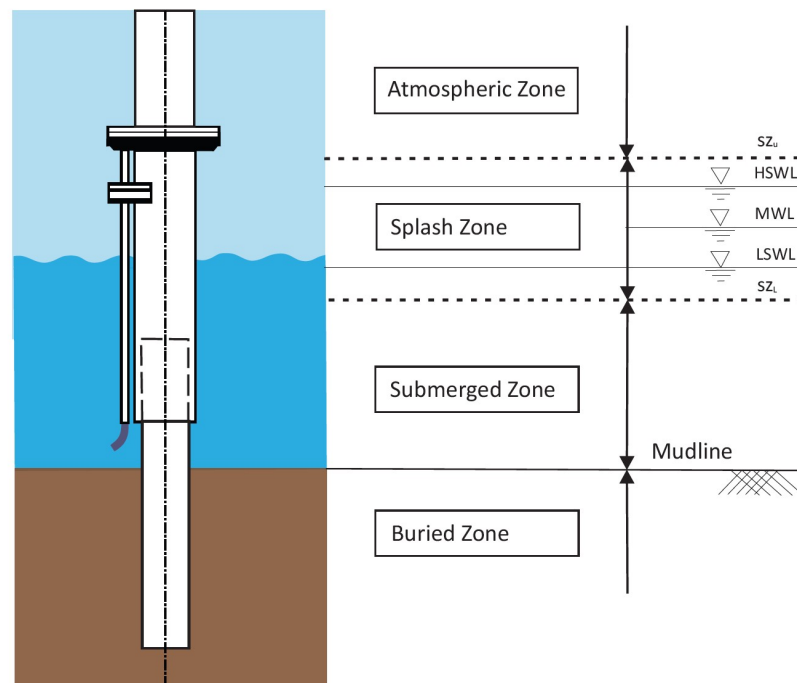


Figure 7. Corrosion control zones (adapted from DNV GL RP 0416, Figure 4-1)

The definition of the splash zone is an important aspect of monopile design because the splash zone cannot effectively be protected with cathodic protection. This is because any cathodic protection system requires the steel to be immersed in seawater. If the steel is not fully immersed in the water,

areas that are expected to be protected via cathodic protection will be exposed to corrosion. This can occur when a design does not properly capture tidal variation. Figure 8 from Section 4.3.2 of DNVGL-RP-0416 defines the splash zone (DNV GL, 2016a).

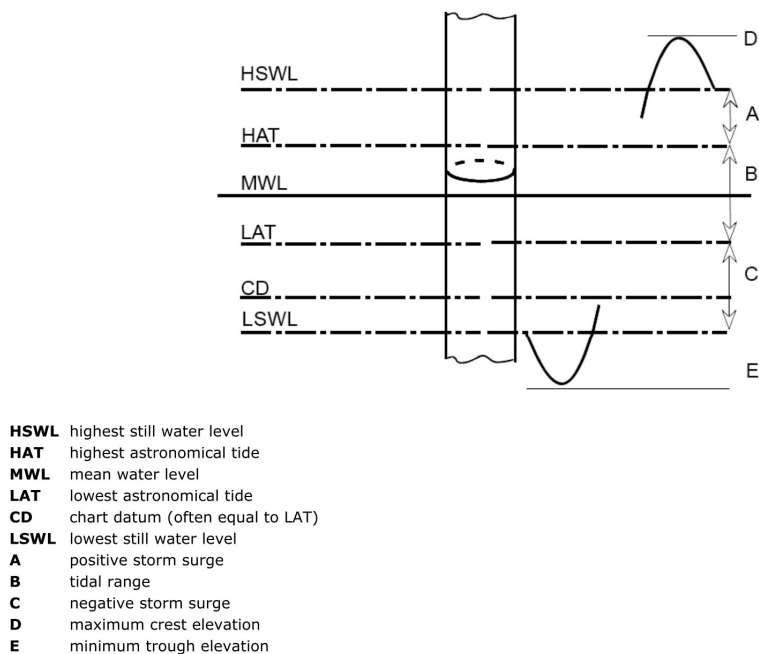


Figure 8. DNV GL splash zone definition (from DNV GL RP 0416, Figure 4-2)

Table 1 shows a comparison of the requirements for corrosion protection across all documents in each of the zones. While more information and comparisons of different design codes can be found in the appendix this chapter will only discuss DNV GL RP 0416. Coating is required in the atmospheric and splash zones because it is the only way to prevent corrosion. Cathodic protection only works on steel below the waterline in the submerged zone. Coating can also be used in the submerged zone to improve their effectiveness. At the mudline coatings are particularly recommended because of the potential risk of MIC.

Table 1 Protections by Zone

Zone	DNV GL RP 0416
Atmospheric	Coating Required
Splash	Coating Required
Submerged	Cathodic Protection Required & Coating Recommended
Mudline	Cathodic Protection Required & Coating Strongly Recommended
Buried	Cathodic Protection Required

2.2.1 Use of Coatings

Protective coatings usually consist of a few layers of epoxy-based coatings along with a polyurethane topcoat and are most important in the splash and atmospheric zones. Coatings need to be effective against high corrosive stress, high salt concentrations, biological effects, temperature changes, and other factors. Great care is required in selecting and applying protective coatings, with high quality control needed for surface preparation, material handling, application, and subsequent handling to prevent damage from abrasion. Other considerations are the length of time between inspections, repair costs, the design life, and the type of coating (reversible, irreversible, non-polluting).

One study examining the coating performance of offshore wind platforms in the water for 15 years determined that overall, the coatings used by the offshore wind industry had performed well (Weinell, Black, Mathiesen, & Nielsen, 2017). Within their paper the one case study that showed an obvious coating failure was Horns Rev 1 where a coating with a low thickness (350 μm) was tested on a platform in 2002. According to Weinell et al., the coating on Horn Rev 1 failed due to a combination of the thin coating and insufficient grinding of the “ceramic extenders” in the paint (Weinell et al., 2017).

Apart from the Horns Rev 1 platform, the other coating systems all appeared to perform well in European wind farms. For example, Figure 9 contrasts the 350- μm coating performance with another monopile with a 1000- μm coating (Weinell et al., 2017). Both monopiles are in their 14th year of service

and the monopile with the 1000- μm coating shows no major corrosion damage while the monopile with the 350- μm coating appears to be freely corroding.



Figure 9. Horns Rev 14-year coating comparison, left: 350 μm ; right: 1000 μm (from Weinell 2017)

Another note from Weinell et al. is that when coatings do fail it is often because of error in application or rather than a problem with the coating system itself (Weinell et al., 2017). This observation is supported by another review of corrosion protection systems from Plagemann & Momber (2018). Figure 10 from their paper shows the causes of corrosion damage that multiple wind farm platforms experienced in the first year of their service lives in Germany (Plagemann & Momber, 2018). According to the study shown in this figure, most of the failures came from defects in the coating. These defects could have come from “edge retention” due to a lack of proper treatment along a weld seam (Plagemann & Momber, 2018). Another major contributor, mechanical damage, occurs during the installation process and can also cause coating damage.

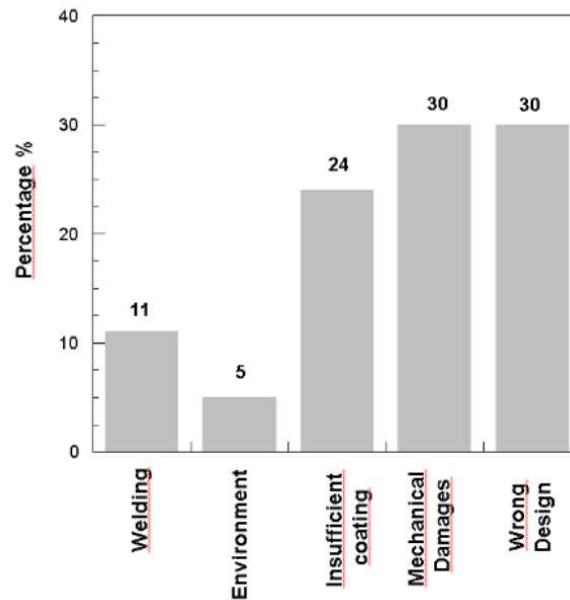


Figure 10. Causes of corrosion damage in the first year (from Plagemann 2018, Figure 3)

Ultimately the lifespan of coating systems used for offshore wind in Europe is a complex question to answer because it is very reliant on the quality control and application of the coating as well as the installation procedure. A coating could have all the correct specifications, but if there is an error in application the platform may have corrosion issues. As the US market develops, proper inspection and QC of the coatings will be key to ensuring that the coatings perform as expected in the design process.

2.2.2 Use of Cathodic Protection (CP) Methodologies

A cathodic protection (CP) procedure was first employed by Sir Humphrey Davy back in 1824, long before its theoretical concept was introduced. CP is a common corrosion protection approach in which the corrosion is mitigated by minimizing the difference between anode and cathode potentials. In a cathodic protection system, an electrical current operates between an outside source up until to the point that the whole component is at one potential without having anode and cathode sites. CP is commonly applied in addition to protective coatings. Cathodic protection can prevent both oxygen-

controlled and microbiologically controlled corrosion. Figure 11 demonstrates a typical cathodic protection circuit for an oil and gas pipeline. The two major types of cathodic protection systems are:

- (i) Sacrificial (or galvanic) anode cathodic protection (SACP)
- (ii) Impressed current cathodic protection (ICCP)

ICCP system uses an external power source with inert anodes, while the SACP performs based on the naturally occurring electrochemical potential difference between parts made up of different metals.

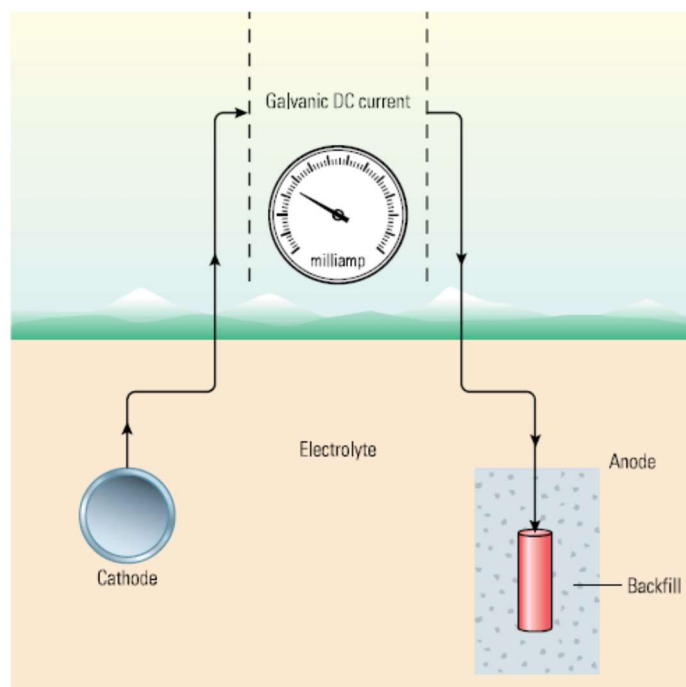


Figure 11. Cathodic protection circuit for a pipeline (Source: Asrar et al., 2016)

2.2.3 Use of Corrosion Allowances

A corrosion allowance is simply excess steel added to the design under the assumption that some corrosion will occur. It is quite common in oil and gas design where the ultimate limit state is more likely to drive the design than the fatigue limit state (DNV, 2012). Corrosion allowances can be a

challenge when fatigue life is a concern because free corrosion conditions greatly reduce the fatigue life of steel, see next section.

2.3 Fundamentals of Fatigue

In addition to corrosion offshore wind monopiles need to survive fatigue damage. Fatigue is defined as the process of crack initiation and growth under cyclic loading. Fatigue damage has been observed and studied for over a century. In a paper titled “Fracture of Metals Under Repeated Alterations of Stresses,” Ewing and Humfrey observed iron under a microscope as fatigue damage accumulated (Ewing & Humfrey, 1903). Ewing and Humfrey observed that as the number of cycles increase, slip bands form in the crystals that make up the metal’s microstructure. The slip bands eventually grew large enough to join and form small cracks. This early study illustrated that fatigue damage accumulation is a consequence of damage on a microstructural level.

Following the crack initiation phase, the second stage of fatigue is called crack growth (Socie & Marquis, 2000). Crack growth can be divided into short crack growth and long crack growth. Short and long crack growth stages are defined as two separate stages in fracture mechanics, and they are governed by different equations and mechanisms. The two general approaches for estimation of fatigue damage are introduced in the following subsections.

2.3.1 S-N Curve Analysis and the Palmgren Miner Rule

The oldest and most common form of fatigue life characterization and assessment is S-N curve analysis. An example of an S-N curve taken from DNVGL-RP-C203 recommended practice “Fatigue Design of Offshore Structures” is presented in Figure 12 (DNV GL, 2016b). An S-N curve is a relationship between the shear stress range on the y-axis and the number of cycles until failure, N, on the x-axis. It is

important to note that both $\Delta\sigma$ and N are plotted on a logarithmic scale. These curves are generated based on experimental data gathered from testing smaller specimens.

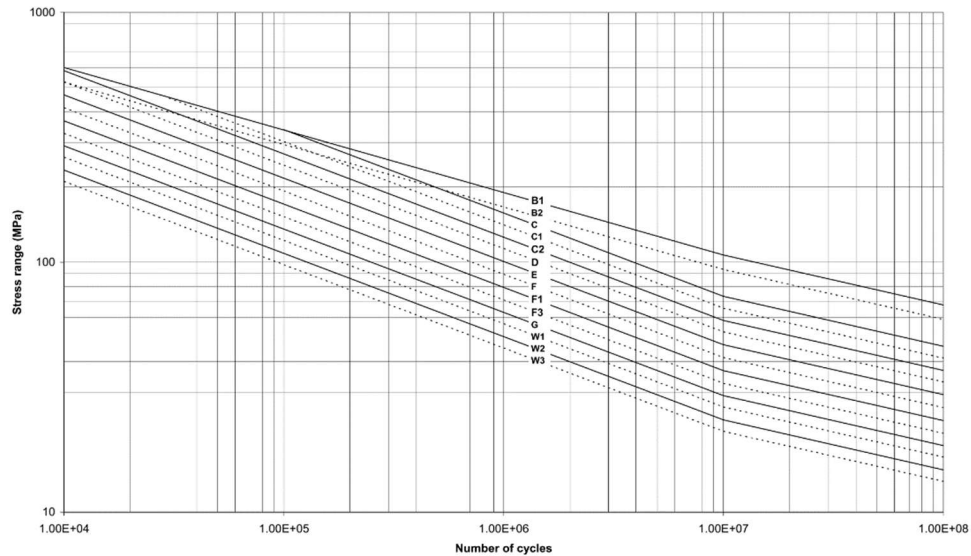


Figure 12. S-N curve recommended by standard DNVGL-RP-C203 (From DNV GL c203, Figure 2-9)

There are three most common cycle counting methods: level crossing, peak cycle, and the rain flow cycle (RFC) counting method. Of these methods, the RFC method is usually considered the most accurate. The biggest advantage is that the RFC accounts for all the peaks without repetition, such that the small amplitude cycles are not excessively considered; this leads to a less conservative estimate of fatigue damage and life. The RFC approach also allows the application of the Palmgren Miner rule in fatigue life assessment of components that undertake complex loading scenarios. Figure 13 from ASTM E1049-85 (1985) presents a common flowchart for the RFC counting method.

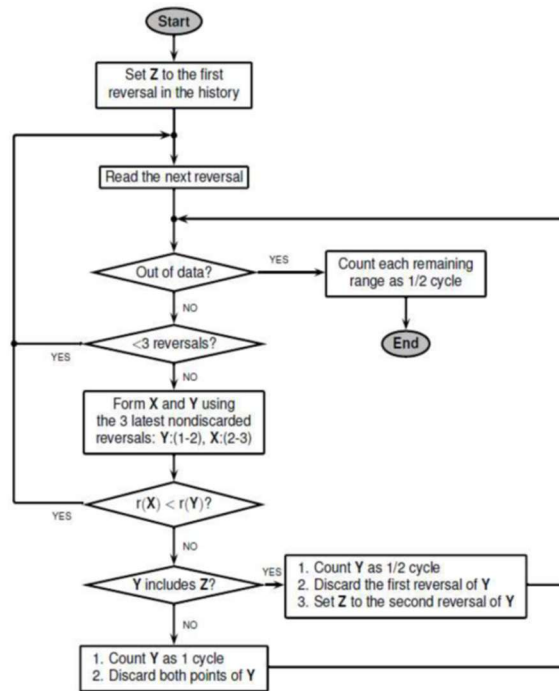


Figure 13. Rainflow algorithm for stress cycle counting (From ASTM E1049-85)

In addition to general S-N curves, DNVGL-RP-C203 provides guidance on generating new S-N curves. The F.7 commentary of C203 describes how to generate an S-N curve with a limited number of physical tests. According to the commentary: “a design S-N curve should provide a 97.7% probability of survival where the mean curve is determined with 75% confidence” (DNV GL, 2016b). With a limited amount of test data meeting this criterion, it is a challenge to create curves, as this requires the use of both statistical consideration and engineering judgement. The challenge of how to weigh different types of fatigue tests from different testing programs must also be considered. A deeper discussion of these challenges can be found in the DNVGL-RP-C203 commentary “F.7 Comm. 2.4.14 Qualification of new S-N curves based on fatigue test data” (DNV GL, 2016b).

For corrosion-fatigue specifically, DNVGL-RP-C203 provides general S-N curves for seawater conditions with cathodic protections and seawater conditions under free corrosion conditions. In S-N curve testing, specimens are tested until failure. Failure for S-N testing is defined by a range that extends

from very early stages of cracking (almost in the crack initiation phase) to well-cracked conditions (e.g., observing cracks with lengths higher than 30 mm). Chapter 4 provides a deeper discussion of failure definition in the context of the testing used to generate the current S-N curves. The definition of failure often depends on the goals and technology used in the testing program.

S-N curves are based on constant amplitude stress and testing. This means that for each specimen, the test uses one stress range (i.e., 100 MPa) until the test ends in specimen failure. Constant amplitude testing is much different than the variable amplitude loading conditions that offshore wind foundations experience during their operational lifetime. To address this difference, most fatigue analyses assume that the fatigue damage accumulates linearly (i.e., the damage from the n^{th} cycle is not dependent on any of the previous cycles). This assumption comes from the Palmgren Miner rule, which is presented in Equation 1 (Miner, 1945):

$$D = \sum_{i=1}^k \frac{n_i}{N_i} \leq \eta \quad \text{Equation 1}$$

where

D = accumulated fatigue damage

k = number of stress blocks

n_i = number of stress cycles in stress block i

N_i = number of stress cycles to failure at constant stress range $\Delta\sigma_i$

η = usage factor which is equal to $1/\text{DFF}$ where DFF is the design fatigue factor defined in the standard from DNVGL-OS-C101 (Sec.6 Fatigue limit states) (DNV GL, 2015).

The Palmgren Miner rule allows simplified constant amplitude testing to be applied to the complex loading conditions that occur in the field. Without the Palmgren Miner rule, unique testing would need to be done to represent different possible loading sequences. The Palmgren Miner rule is widely accepted for fatigue analysis, but tests show that load sequencing does influence fatigue life. Ultimately, the Palmgren Miner rule is an imperfect assumption that is used to make fatigue life analysis practical.

2.3.2 Fracture Mechanics and the Paris Law Equation

Linear elastic fracture mechanics (LEFM) applies the theory of elasticity to estimate the fatigue life of cracked and defected bodies. The basic assumptions of LEFM are built on small displacements and a linear relationship between stresses and strains. LEFM relates the stress magnitude and distribution near the crack tip to the size and shape of the crack, material properties, and nominal (not local) stress applied to the cracked component. Since fracture mechanics requires the initial size of a crack (or an estimation), fracture mechanics approaches are used to estimate the fatigue life in the crack propagation stage.

The most common model for fatigue crack propagation is the Paris Equation (also known as the Paris law). The Paris Equation is an empirical relationship that relates the stress intensity factor range with the rate of crack growth per cycle. The following equations and figures come from BSI-7910, “Standards Publication Guide to Methods for Assessing the Acceptability of Flaws in Metallic Structures” (BSI, 2015):

$$\frac{da}{dN} = A(\Delta k)^m \quad \text{Equation 2}$$

where

$$\frac{da}{dN} = \text{fatigue crack growth rate}$$

A = material constant (sometimes represented as C)

m = also a material constant (often taken between 3.0 and 4.0 for metals)

Δk = stress intensity range, which is defined by following equation:

$$\Delta k = Y(\Delta\sigma)\sqrt{\pi a} \quad \text{Equation 3}$$

where

a = crack length

Y = correction factor which depends on crack geometry

$\Delta\sigma$ = stress range

Finally, the Paris Equation is integrated to get the crack size in relation to the number of cycles:

$$\int_{a_i}^{a_f} \frac{da}{Y^m (\pi a)^{m/2}} = A(\Delta\sigma)^m N \quad \text{Equation 4}$$

Similar to S-N curves, the Paris Equation is based on experimental data. The A and m terms are determined experimentally. Unlike S-N curve testing, fracture mechanics tests are performed on pre-cracked specimens. This is because the Paris Equation cannot be used to model crack initiation; it can only be used to model crack growth. The relationship described by the Paris Equation is often represented in experimental testing by plotting $\frac{da}{dn}$ vs Δk . Compared to testing to generate S-N curves, fracture mechanics tests are much quicker to conduct because they only examine the crack growth phase. As a result, there is more test data available defining A and m . For example, in Chapter 4 much of the crack growth data comes out of the SLIC project tests. These tests account for some differences between old testing and modern testing such as steel types and a focus on the heat affected zone. For crack growth modeling with fracture mechanics, the thickness does not have a direct impact, but the

residual stresses are important in the form of the loading ratio R . For more information, see Chapter 4.

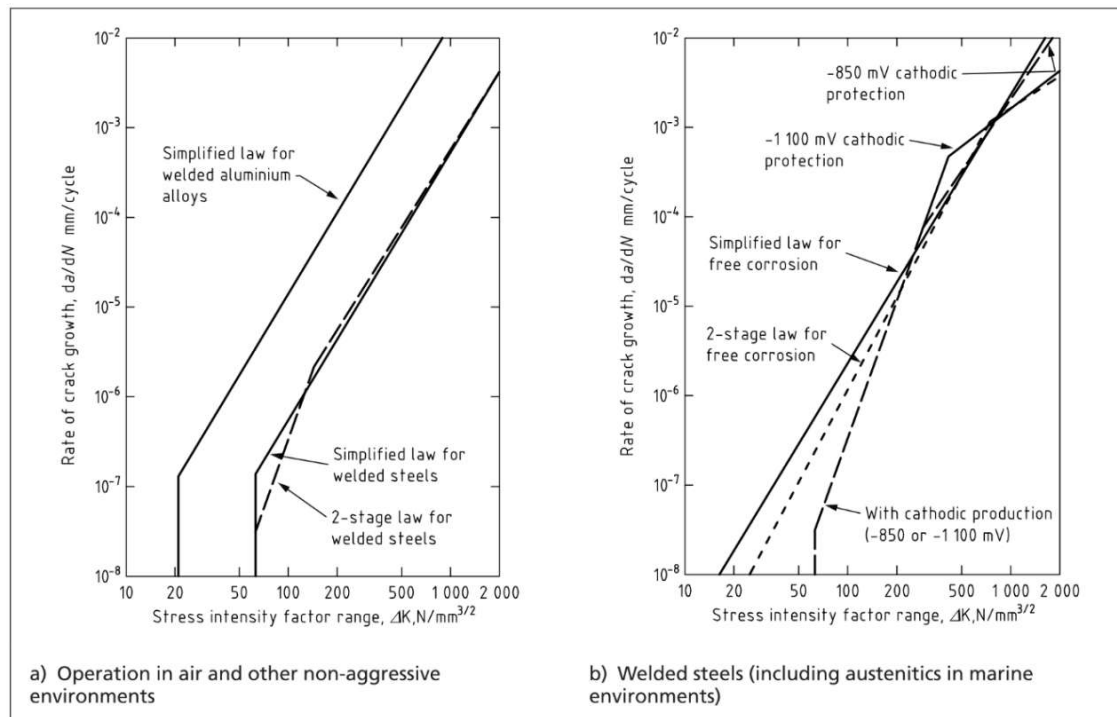


Figure 14. Sample fatigue crack growth curves: (a) non-aggressive environment, (b) marine environment

As mentioned, S-N curve analysis relies on the Palmgren Miner rule to relate constant amplitude testing with variable amplitude operating conditions. The fracture mechanics approach also needs to account for variable amplitude loading. According to BSI-7910 (2015), use of the Paris law (Equation 2) may overestimate fatigue life under variable amplitude loading, so the calculated fatigue life should be halved for critical conditions (BSI, 2015).

According to DNVGL-RP-C203, there are three main cases where fracture mechanics is recommended (DNV GL, 2016b):

1. "Assessment of acceptable defects"
2. "Evaluation of acceptance criteria for fabrication"
3. "Planning in-service inspection"

Overall, fracture mechanics analysis is very valuable for cases where an initial defect size a_0 is known. However, in most cases the initial defect size is not known. Chapter 5 gets into more detail about the use of LEFM vs SN techniques in remaining useful life assessments.

2.3.3 Corrosion-Fatigue Interactions

Research funded by the U.S. Office of Naval Research in the 1980s investigated the corrosion-fatigue interaction and described the process as a combination of three parts (Wei & Simmons, 1981):

1. A pure fatigue damage component
2. A damage component related to the environmental/loading conditions
3. A damage component related to stress corrosion cracking

Generally, for marine steels the stress corrosion cracking component is seen as negligible. As for other fatigue life cases, it is useful to break up the corrosion-fatigue life of steel into two main phases with different damage mechanisms: crack initiation and crack growth/propagation. Most of the research on corrosion fatigue damage accumulation has focused on the crack propagation stage. Several fracture mechanics tests on compact tension specimens have documented that cracks grow faster under corrosive conditions than under pure fatigue conditions. The effects of corrosion fatigue damage viewed from a mechanistic perspective are discussed in Chapter 5, while a deeper discussion on existing test data is discussed in Chapter 4.

Combining the two phases of damage accumulation is one of the challenges of design, and different methods for modeling corrosion-fatigue have different ways of combining the two phases. Methods include S-N curve analysis, fracture mechanics analysis, calibrated fracture mechanics analysis, and probabilistic mechanistic modeling. The models will be reviewed in more depth in Chapter 4.

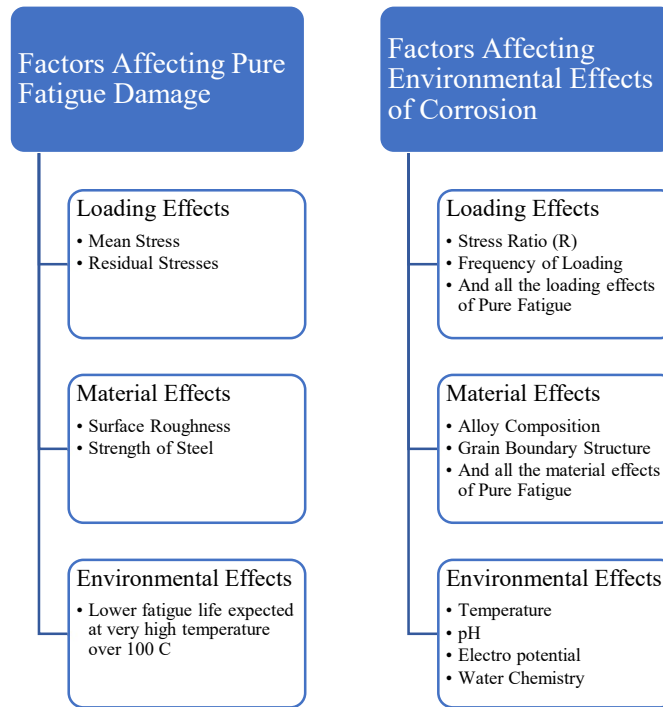


Figure 15. Comparison between pure fatigue damage and corrosion fatigue damage

One major difference between corrosion-fatigue damage accumulation and pure fatigue damage accumulation is that corrosion-fatigue damage accumulation incorporates significantly more input variables. A summary of these variables is presented on the left side of Figure 15. A significant amount of time was spent studying the impact of environmental and loading conditions in the 1970s and 1980s. Although the tests are now dated, they cover a wide range of testing conditions and are quite valuable. The effects of these variables are reviewed in Chapter 4.

The different stages of corrosion-fatigue crack growth are affected by corrosion differently because of different damage mechanisms. A paper from Gkatzogiannis et al. described the effect of corrosion on the fatigue process, which can be seen in Figure 16 (Gkatzogiannis, Weinert, Engelhardt, Knoedel, & Ummenhofer, 2019). A major challenge when describing corrosion-fatigue is the complexity of the interaction between different variables. This will be discussed in detail in Chapter 4.

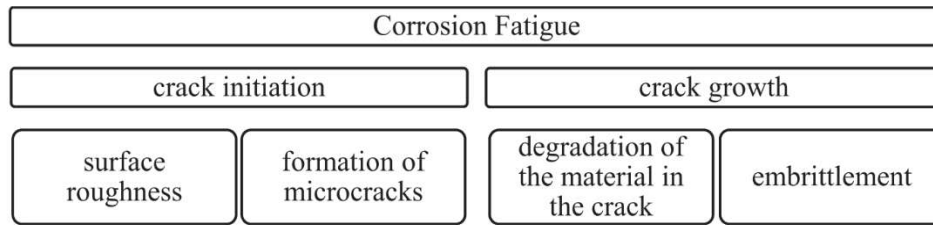


Figure 16. Different stages of corrosion fatigue

2.4 Conclusion and Key Findings

This chapter provides background information about offshore wind turbine foundation design with a focus on corrosion and fatigue design. While some of the information in this section will be repeated in chapters 3-6 the purpose here is to give technical definitions and backgrounds for specific terms and convey why corrosion, fatigue, and the combination of the two in the corrosion-fatigue process are important for offshore wind design.

Key Findings:

- The earliest generation of offshore wind monopiles built from 2002-2009 had design issues. While there are conference papers reporting these issues and summarizing the impacts of retrofitting efforts, the entire story has not been compiled in one review. The two main failures were:
 - The grouted connection between the monopile and transition piece failed due to fatigue loading.
 - The designs assumed that the inside of monopiles were sealed and thus no internal corrosion was present. When this assumption was proven to be faulty there were severe corrosion issues inside of monopiles. (Details in Chapter 3)

- The internal corrosion issue highlights the interdisciplinary nature of offshore wind monopile design. Corrosion and fatigue damage are two different mechanisms of damage but when they are combined into the
- For example, this historical issue with monopile design corrosion occurs and then corrosion protection is applied creates a problem from a corrosion-fatigue damage modeling standpoint.

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Chapter 3 Corrosion Challenges & Details

3.1 Introduction & Timeline

One barrier to the deployment of Offshore Wind energy in the US is the availability of local workers, designers, and subject matter experts. Constant et al. 2021 identified a significant shortfall in the preparation of engineers in the U.S. to design this new form of heavy infrastructure. As engineers are trained to work in the new offshore wind market, the highly interdisciplinary nature of offshore wind foundation design needs to be considered. Corrosion protection solutions inside of offshore wind monopiles is one such area where there are significant overlaps between corrosion engineering, structural engineering, and environmental engineering disciplines. To investigate the multidisciplinary nature of these overlaps, this review is structured into three sections:

1. Timeline of Internal Corrosion Experience in Europe
2. Overview of the State of the Practice for Internal Corrosion Protection
3. Identification of Future Research Needs and Disciplinary Overlaps

Figure 17 presents a timeline of corrosion studies for offshore wind monopiles. The black text identifies conference papers and presentations while the red text identifies design guidance documents. The timeline is broken into three eras: early monopile design, learning period, and current design. The early monopile designs era covers over 500 two-part monopile foundations installed with a simple grouted connection between the monopile and transition piece from 2002-2009 (Jensen et al., 2018). After 2009, settlement in some of the foundations due to weakening grouted connections was observed; and the designs needed to be re-evaluated (Jensen et al., 2018). When the interiors of these foundations were inspected, higher than expected corrosion rates were also identified inside of the monopiles

(Hilbert et al., 2011). Thus begins the learning period when the industry learns about internal corrosion issues around 2009. This period ends in 2016 after the publication of DNVGL-RP-0416 Recommended Practice for Corrosion Protection of Wind Turbines; this was the first design guidance document that identified internal corrosion issues for monopiles specifically (DNV, 2016). In the current practice period, the need to consider internal corrosion is properly identified in design documents, but there is still less guidance than for external cathodic protection (CP). For example, a 2017 presentation concluded that the standards at the time did not give any guidance on corrosion protection design inside of a monopile (Sørensen, 2017). This grey area created an environment for robust debate about the best way to protect the insides of monopiles from corrosion.

The Offshore wind industry has not always fully appreciated corrosion risk. The original incorrect assumption that internal compartments would be sealed is a good example but only part of a broader trend (Hilbert et al., 2011). There have also been issues with some external corrosion protection systems because the corrosion protection designs were designed by individuals without sufficient experience in designing corrosion protection systems, which were seen as low priority tasks (Wyatt et al., 2020). In the current era, asset owners and foundation designers are more aware of the importance of corrosion because of the expensive lessons from the first era of monopiles. However, there is evidence that the industry is not confident in their ability to quantify the cost of corrosion. In a recent industry survey, 27 out of 30 respondents said they did not have a clear view on how the capital (CAPEX) costs of protecting against corrosion related to the maintenance costs of corrosion (OPEX) for ocean energy devices (Tacq, 2021). While the importance of corrosion is more recognized as seen by the extensive amount of research done in f, there is still work to be done quantifying the impact of a robust corrosion protection design for the overall project.

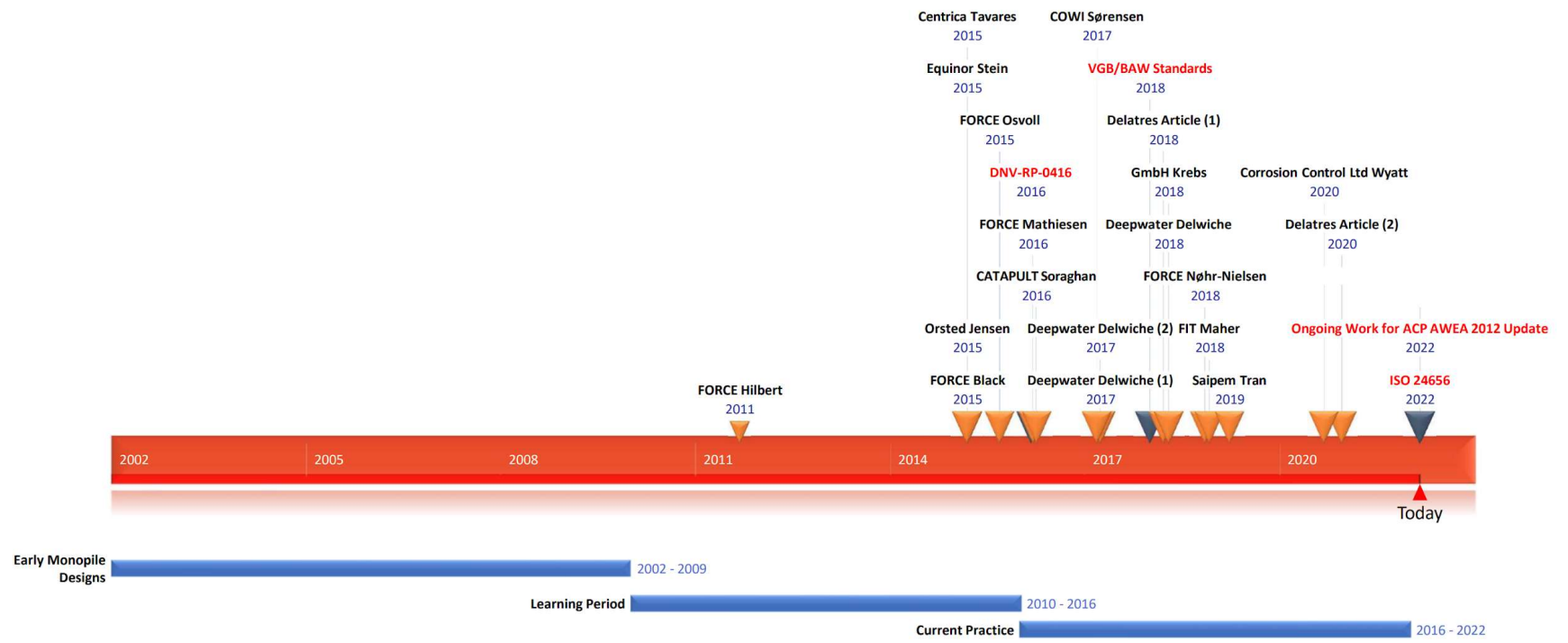


Figure 17 Timeline of Internal Corrosion Issues for Offshore Wind Monopiles

Table 2 Documents Identified in Timeline (Figure 1)

Timeline Name	Month/Year	Doc Type	Reference
FORCE Hilbert	09/2011	EuroCorr Conf. Paper	(Hilbert et al., 2011)
FORCE Black	03/2015	CORROSION Conf. Paper	(Black et al., 2015)
Orsted Jensen	03/2015	CORROSION Conf. Paper	(Jensen, 2015)
Equinor Stein	03/2015	CORROSION Conf. Paper	(Stein et al., 2015)
Centrica Tavares	09/2015	EuroCorr Conf. Paper	(Tavares et al., 2015)
FORCE Osvoll	09/2015	EuroCorr Conf. Paper	(Osvoll et al., 2015)
DNV-RP-0416	03/2016	Recommended Practice	(DNV, 2016)
FORCE Mathiesen	03/2016	CORROSION Conf. Paper	(Mathiesen et al., 2016)
CATAPULT Soraghan	04/2016	Report	(Soraghan, 2016)
Deepwater Delwiche (1)	03/2017	CORROSION Conf. Paper	(Delwiche et al., 2017)
Deepwater Delwiche (2)	03/2017	CORROSION Conf. Paper	(Delwiche and Tavares, 2017)
COWI Sørensen	03/2017	IPQC Presentation	(Sørensen, 2017)
VGB/BAW Standards	01/2018	German Standards	(VGB PowerTech, 2018a)
Deltares Article (1)	03/2018	Web Article	(Deltares, 2018)
Deepwater Delwiche	04/2018	CORROSION Conf. Paper	(Delwiche and Lydon, 2018)
GmbH Krebs	04/2018	CORROSION Conf. Paper	(Krebs, 2018)
FORCE Nøhr-Nielsen	11/2018	GfKORR Conf. Paper	(Nøhr-Nielsen, 2018)
FIT Maher	12/2018	Thesis	(Maher, 2018)
Corrosion Control Ltd Wyatt	09/2020	CORROSION Conf. Paper	(Wyatt et al., 2020)

Deltares Article (2)	12/2020	Web Article	(Deltares, 2020)
ISO 24656	05/2022	International Standard	N/A
ACP AWEA 2012 Update	06/2022	U.S. Standards	N/A

Figure 17 shows that it takes time for information to percolate through the community. First, an issue is identified by asset owners based on their field observations. Then this information is often disseminated a few years later via conference papers and finally it is placed into formally recommended practice documents by the industry. For example, it is now well established that aluminum anodes placed inside of a sealed monopile will drop the pH of the internal water column without proper water replenishment, and cause issues with the cathodic protection system. Much of the public knowledge about this fact can be traced back to a 2012 retrofit of an existing monopile structure that was formally described in a 2017 conference paper (Delwiche and Tavares, 2017). While 2017 was the first formal review of the retrofit done by the team that deployed it, the 2012 retrofit was also discussed in the context of two lab studies in 2015 that investigated the effects of aluminum anodes in a sealed system (Soraghan et al., 2015; Tavares et al., 2015). It took five years from 2012 to 2017 for a full conference article about the field deployment of retrofitted aluminum anodes even though the issues were being investigated in the lab as early as 2015. This time lag is particularly important in a fast-growing sector like the US offshore wind industry where there are new technical challenges, new metocean conditions, new companies entering the space, and new workers.

This time lag has also continued into the current era. Different internal corrosion protection design schemes are being used but have not been formally published. Conversations with different designers and asset owners have revealed that perforating the monopile to allow for natural water replenishment is a common design choice. However, details about the performance of perforated monopiles are very limited. As a result of the limited amount of public research literature, it is necessary to supplement the understanding of internal corrosion issues via workshops with industry practitioners.

In addition to this time lag, internal corrosion issues are an excellent example of the interdisciplinary nature of offshore wind foundation design. While the primary focus of these perforation holes is to replenish water for the internal CP system, they also have a cascade of effects on other aspects of a foundation. Figure 18 demonstrates how perforations can intersect with the corrosion protection system design, structural design, and environmental effects.

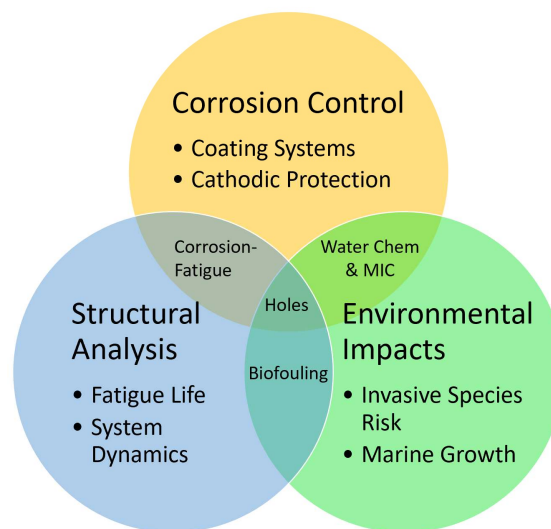


Figure 18 Interdisciplinary Monopile Framework

3.2 Monopile Internal Corrosion Control Review

Internally or externally, there are two primary methods for corrosion protection: coatings and/or CP systems, and the combination of methods used is dependent on the location on the structure. Figure 19 shows a monopile with the corrosion zones labeled according to definitions found in DNV-RP-0416. For corrosion protection, the splash zone and submerged zone are key (DNV, 2016). The splash zone, sometimes called the intertidal zone, needs to be protected from corrosion using a coating system because CP only works when the steel is submerged in water. The submerged zone is protected using a CP system, but a coating may be used in combination with the CP system of choice.

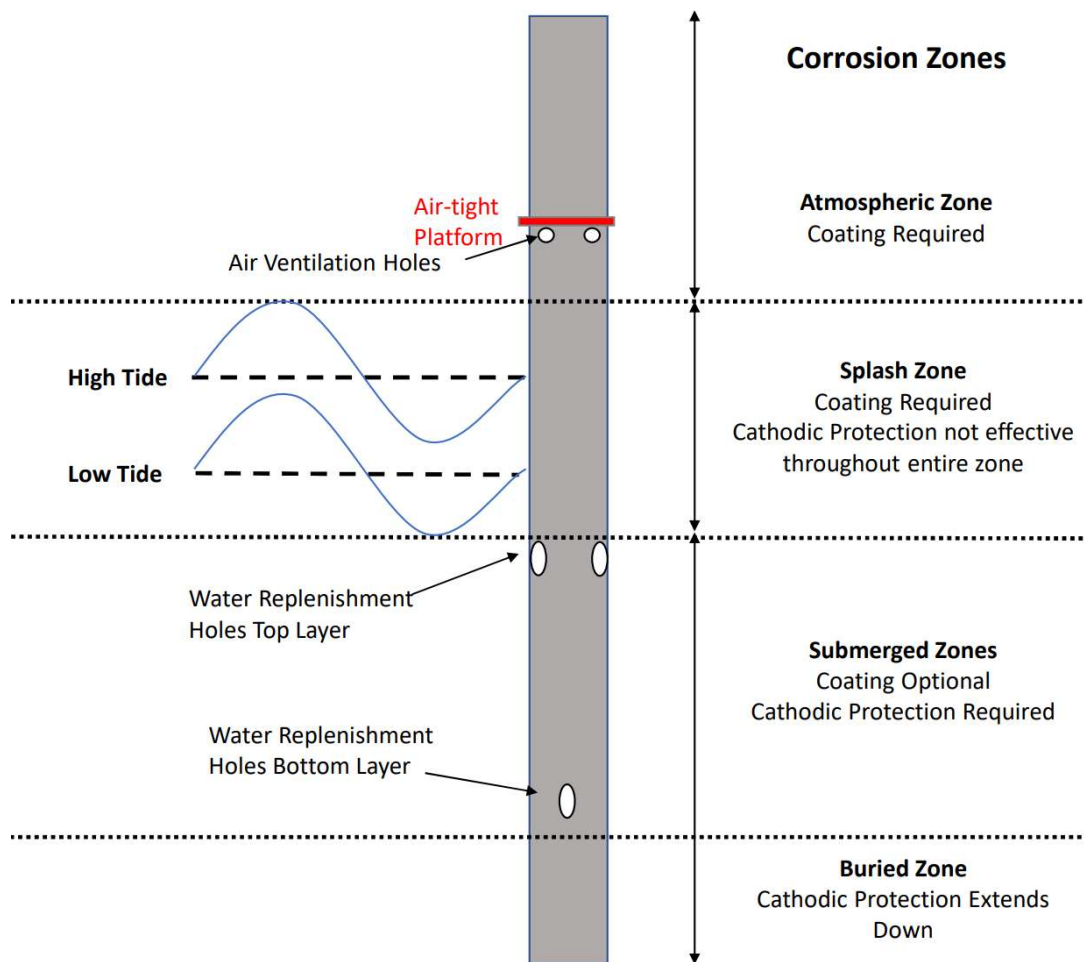


Figure 19 Diagram of monopile with corrosion zones and theoretical perforation placements

Corrosion occurs when electrons flow from anode to cathode in the steel. Cathodic protection works by controlling the direction the electrons flow. Electrons are fed into the structure from an external source (i.e., anode) so that the whole structure becomes the cathode. There are two main categories of CP: galvanic anode systems and ICCP systems. In galvanic anode systems, the electron source is a different metal such as zinc or aluminum and these metal anodes are consumed over time. In ICCP systems there is an external power source, and the anode is a material such as a mixed metal oxide (MMO) designed to resist corrosion. Anode selection is a key decision point for a CP system affecting key variables such as the mass of the system, long term system reliability, and performance with low levels of

water replenishment. The chemical products produced by different CP systems will be reviewed later in this article since these products have the potential to cause issues inside of a partially sealed system such as an unperforated monopile.

In addition to a CP system, the other main tool for preventing corrosion damage is coatings. When coatings are used in the submerged zone, their role is to reduce the current density needed to protect the structure. In the case of galvanic systems coatings help the anodes last longer and will reduce the total anode mass needed for a design. In a conceptual design of an external aluminum anode CP system, (Erdogan & Swain, 2021) found that depending on the external coating the minimum anode mass was as high at 18,000 kg for an uncoated monopile and as low as 5600 kg for a coated monopile.

To get a picture of the internal corrosion protection practices, the design process can be broken into three key decisions. First, the designer chooses to use an internal coating in the internal submerged zone or not. Second the design can either use no anodes, zinc anodes, aluminum anodes, or ICCP anodes for CP. Third the design can either use a perforated monopile designed to replenish the internal water column naturally or it can be unperforated and treated as a semi-sealed system with some oxygen ingress. These three options create sixteen total potential combinations.

3.2.1 Comparison of Standards Related to Internal Corrosion Control

As discussed briefly in section 1.2, there is little guidance related to internal corrosion protection for monopiles in the documents related to corrosion protection system design. Three design guidance documents mention internal corrosion as a specific issue for design: DNV-RP-0416, VGB/BAW Series, and ISO 24656. DNV-RP-0416 Corrosion Protection for Wind Turbines is the recommended practice for corrosion protection published in 2016 by the certification verification agent DNV (DNV, 2016). The VGB/BAW standards from the German regulator for offshore wind are divided into four parts and were

published in 2018 (VGB PowerTech, 2018b, 2018a, 2018c, 2018d). Finally, ISO 24656 Cathodic Protection for Offshore Wind Structures was published in 2022.

There are several general points where all three design guidance documents agree. First, all three recognize that the inside of the monopile should not be treated as a fully sealed system that does not need corrosion protection. Second, all recognize that for aluminum anodes water replenishment is required to prevent the internal water column from acidifying. Third, all provide language related to the three key decisions described earlier coatings, anode selection, and water replenishment. While this language is subtly different from document to document, it is typically not prescriptive. This is particularly noticeable for water replenishment decisions where there are no specific guidelines or examples for how to consider this aspect of the design.

For coatings, DNV-RP-0416 states that an internal coating in the submerged zone is optional while the VGB/BAW series requires an internal coating (DNV, 2016; VGB PowerTech, 2018a). For anode selection, there are subtle differences in the language between DNV-RP-0416 and VGB/BAW. DNV-RP-0416 specifically states that if water replenishment is not possible, zinc anodes are recommended, and ICCP systems are not mentioned, while the VGB/BAW series do not discuss zinc and instead suggest using ICCP. The VGB/BAW requirements also mention that for an ICCP system the main concerns are hydrogen and chlorine gas generation.

3.2.2 Different Options for Internal Corrosion Control

After reviewing design documents and engaging with the industry community via several workshops, the sixteen potential combinations were narrowed down into three clusters of internal corrosion control. The first cluster is unperforated monopiles, coated, with no CP. The second cluster category is unperforated monopiles, coated, and with CP. The final cluster is perforated monopiles, coated, and with CP. In conversations with designers at workshops a few trends were identified.

Perforations were popular, and the only unperforated monopile selection used a coating and zinc corrosion protection system.

Another common option discussed was unperforated coated monopiles with zinc CP, which was expected since that option is described in DNV-RP-0416 (DNV, 2016). Coatings are also very commonly seen in all designs even though they are technically optional according to DNV-RP-0416. This makes sense because as mentioned earlier coatings are very effective at reducing the total anode mass needed for a design. Anode mass and the number of anodes is particularly important to minimize for internal corrosion protection systems where space, transportation costs, and staging areas come at a premium.

One unexpected result of workshop discussions was the popularity of ICCP for internal compartments since it is not specifically recommended in DNV-RP-0416 (DNV, 2016). However, ICCP is mentioned in the VGB/BAW series, and there is also other evidence indicating the use of internal ICCP systems (VGB PowerTech, 2018d). For example, in their 2017 presentation on internal corrosion protection, Sørensen concluded that internal ICCP systems were a good choice (Sørensen, 2017). There is also evidence of a retrofit to replace a poorly functioning aluminum anode CP system with ICCP system on 38 monopile foundations in 2016 (Krebs, 2018).

Beyond the use of specific systems, one key theme from the workshops was the general importance of reliability, regardless of internal or external placement. Different designers and asset owners have varying levels of comfort with using ICCP systems because of concerns about long term reliability. Signs of this reliability debate show up in the VGB/BAW standards that say zinc and aluminum anode systems have very small efforts for maintenance while ICCP systems have great efforts for maintenance (VGB PowerTech, 2018d). The viability of internal ICCP CP systems is a matter of some debate in the industry. Ultimately, system selection is context dependent and the level of comfort the asset owners and designers have matters.

The popularity of perforations for water replenishment was not surprising, but it does pose a challenge for this review because there are no public papers on perforations for water replenishment. The best written evidence of perforations comes from two online articles on the website for Deltares, an independent research institute in the Netherlands (Deltares, 2020, 2018). In addition to these web articles, a master's thesis that looks at perforations; however, the thesis is unique in that it considers water replenishment requirements for a zinc CP system (Andersen, 2017). This is the only source identified that implies a zinc CP system would need perforations for water replenishment. One likely reason this thesis is an outlier is because its focus was to study the flow of water in and out of a perforated monopile and the anode selection and CP was only a motivation for the fluid modeling (Andersen, 2017). Finally, (Tran et al., 2019) proposed a system with two check valves to provide water replenishment of about 5% to 20% per day for drilled piles. Drilled piles pose a unique challenge for water replenishment because the mudline outside of the pile is higher than the mudline inside of the pile which creates a cavity for stagnant water that needs to be circulated.

3.2.3 Role of Water Chemistry

As alluded to in earlier discussions about aluminum anodes and acidification, the water chemistry inside of unperforated monopiles is a key variable for internal corrosion protection systems. Both lab and field experiments have studied the changes in water chemistry inside the monopiles including pH changes, differential aeration, and the generation of dangerous gases. Three distinct types of CP systems are possible options: aluminum anodes, zinc anodes, and ICCP. The effects of these systems on water chemistry are summarized in Table 3. Table 3 is adjusted from a past review of internal CP systems (Wyatt et al., 2020) with additional points added based on a literature review and conversations from workshops held by the team.

Table 3 Anode Selection Impact on Internal Water Chemistry

	Al	Zn	ICCP
Water acidification due to significant pH drop	X	-	-
Oxygen reduction on cathode	X	X	X
Dangerous gas generation			
Hydrogen production	X	X	X
Chlorine gas production	-	-	X
Calcareous deposit formation (no replenishment)	-	X	X
Replenishment required			
Water	X	-	X
Air	X	X	X

What is known about the water chemistry inside of monopiles comes from a mix of field observations and small-scale lab testing. While a few field observations on retrofitted wind farms have made it into the public literature, there is not currently literature available about the performance of a recent monopile corrosion protection system that is not a retrofit. (Tavares et al., 2015) reported measurements from inside a monopile in the North Sea that was retrofitted with an aluminum anode CP system in 2012; variables such as potential, anode current output, current density, pH, and dissolved oxygen concentration were measured across three months. (Delwiche and Tavares, 2017) retrofitted monopiles in Lynn and Inner Dowsing (LID) wind farm located off the East Lincolnshire coastline with aluminum anodes in 2012 and measured the potentials of the structure, potentials of the anode strings,

pH, dissolved oxygen, and current density. In a separate conference paper about the same retrofit, the ionic composition of seawater inside and outside the monopile protected with aluminum anodes was analyzed (Delwiche et al., 2017). (Delwiche and Lydon, 2018) investigated the pH and gas evolution when internals of monopiles were protected with aluminum and zinc anodes. In the literature, it is not clear if the data analyzed in the Tavares study is from the same farm as the data used in the Delwiche studies, but both use a wind farm retrofitted with internal aluminum anodes for CP. (Krebs, 2018) investigated the effects of using mixed metal oxide (MMO) anodes with ICCP CP systems inside monopiles and reported the differences between MMO and magnetite anodes. Krebs also measured the required current densities inside monopiles and calculated the amount of chlorine gas that may be generated.

In addition to field observations, lab studies were done to better understand the impact of the CP systems on local water chemistry. (Tavares et al., 2015) studied these changes with carbon steel plates placed in pipes and filled with seawater collected from the Anglesey coast, Wales, UK. These pipes could be adjusted to allow for a small amount of flow to simulate water replenishment. The study compared zinc and aluminum anodes and measured potentials and mean current densities of the CP system to determine effectiveness as well as environmental effects such as water pH, bicarbonates in the water, and oxygen concentration. A similar study was also done by (Stein et al., 2015) with two different length carbon steel pipes protected by cylindrical aluminum or zinc anodes. The pipes with 500 mm height were filled only with natural seawater, whereas the pipes with 1500 mm height were filled with mud from shoreline up to 1000 mm and the rest was filled with natural seawater. They measured the initial and mean current densities, and anode capacities for both aluminum and zinc anodes. In addition to these lab studies, (Maher and Swain, 2019) conducted a small-scale field experiment to investigate the effects of perforations on water chemistry and the enhancement of marine life within 152mm diameter steel pipe that was freely corroding or protected by zinc anodes. They measured the temperature, salinity, pH, and dissolved oxygen inside the steel piles in natural waters for two months.

The anode selection for the CP system is a key variable when determining the impact of the corrosion protection design on the internal water chemistry of a monopile. Key results and observations from these various field and lab studies are described in the following.

Aluminum Anodes

The seawater in sealed steel pipes protected by aluminum anodes showed a decrease in pH from approximately 8 to 4. The dissolved oxygen content in solutions decreased, whereas the protection potential, current densities and anode current output all increased. It was concluded that the acidification due to aluminum anodes is a result of both an increase in aluminum ion concentration as well as the reduction of bicarbonate concentration inside monopiles. (Tavares et al., 2015) recommended 10% water replenishment rate with each 'tide cycle' to keep the pH levels at 6 when aluminum anodes are used. (Delwiche and Tavares, 2017), on the other hand, recommended that 5% water flushing per day would be sufficient to avoid acidification issues.

Zinc Anodes

The studies with zinc anodes showed that the water pH decreased approximately from 8 to 7 and samples were cathodically protected without signs of corrosion. (Maher and Swain, 2019) concluded at the end of their field deployment that the test samples were free of corrosion and that there was a buildup of ZnCO_3 on the sealed cathodically protected pipe.

Impressed Current Cathodic Protection

The pilot study on ICCP systems inside the monopiles by (Krebs, 2018) showed that initial, mean, and final current densities were significantly lower than those recommended by standards. The design current densities for the pilot structure were 150, 80 and 90 mA/m^2 for initial, mean, and final,

respectively. However, the measured initial current density was 50 mA/m², mean current density was 15 mA/m² and final current density was 50 mA/m².

Generation of Dangerous Gases

The production of dangerous gases (i.e. Hydrogen Sulfide, Chlorine, and Hydrogen) is a potential major health and safety risk for monopile internals. (Tavares et al., 2015) measured hydrogen sulfide (H₂S) in a sealed experimental setup with aluminum anode and no replenishment. (Delwiche and Tavares, 2017) experienced the existence of H₂S when they opened the airtight hatch to collect water samples from a monopile retrofitted with aluminum anode for almost six months. In 2013 H₂S was also identified in the turbine structure at the Teesside wind farm because the seals in the airtight platform around the cable hang-offs failed and the ventilation system was not fit for purpose (Soraghan, 2016). (Krebs, 2018) also highlighted that low current densities are required to polarize internal steel to protection potentials and that chlorine and hydrogen gas generation is a risk with ICCP systems when MMO anodes are utilized.

3.2.4 Role of Coatings

Although there is not any data on the performance of coatings inside of offshore wind monopiles, there is a large body of research about the overall performance of external coatings. For coatings in the submerged zone, the coating breakdown factor (CBF) is a key variable that estimates the coating performance over time. All coating breakdown factors in DNV-RP-B401 are linear equations as seen in Equation 5 (Lønvik et al., 2019). Historically DNV had three categories of coatings for their coating breakdown factors but a fourth coating category was introduced as a part of the most recent release of B401 in 2019 (Lønvik et al., 2019). Table 4 provides the y-intercept and slopes defining the coating breakdown factors from DNV-RP-B401 and Figure 20 compares the equations for different coating categories from zero meters to thirty meters.

$$f_c = a + b * t \quad \text{Equation 5}$$

Table 4 Coating Breakdown Factor Values from DNV B401

	Cat I	Cat II	Cat III	Cat IV
a	0.1	0.05	0.02	0.02
b [0<d<30]	0.1	0.025	0.012	0.008
b [d>30]	0.05	0.015	0.008	0.005

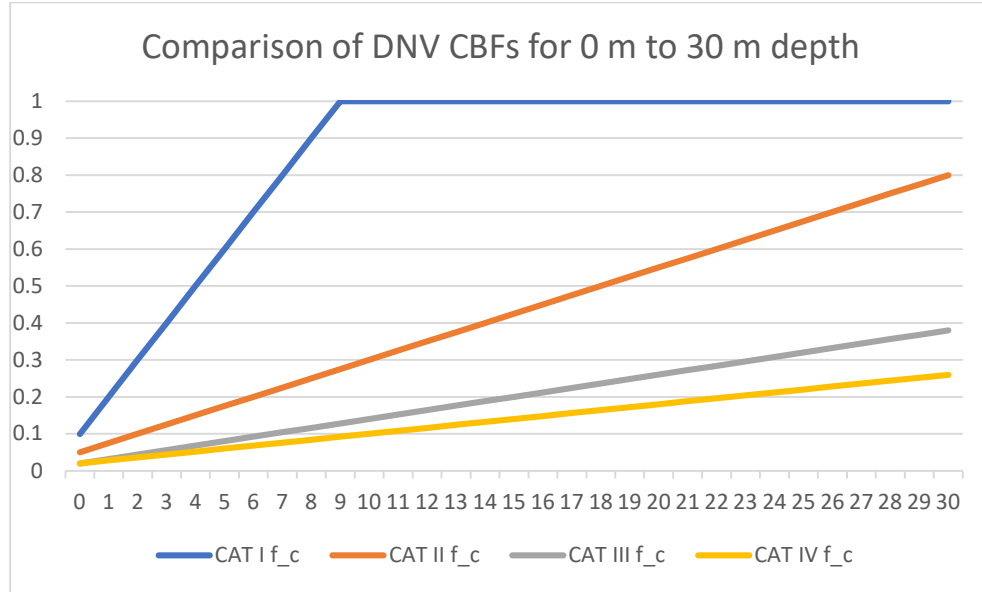


Figure 20 Coating Breakdown Factor Comparison (Shallow Water)

One key reference related to the new coating category in B401 is a 2015 review of coating performance based on a series of field reviews from offshore jacket structures (Lønvik et al., 2019). In this review, the authors inspected four jacket installations; one which had been decommissioned and three that were still in the field (Knudsen and Olsen, 2015). These inspections revealed that the coating breakdown factors for category III coatings in DNV-RP-B401 were overly conservative in all cases. However, the same review of anode consumption found that when the coating breakdown factor was adjusted to account for the observed coating quality, the actual anode consumption was higher than the expected anode consumption based on the adjusted coating breakdown factor. The authors speculated that the very conservative coating breakdown factors may have hidden other aspects of the design that

were unconservative such as the interaction with additional steel attached to the structure such as the steel in the oil and gas wells (Knudsen and Olsen, 2015).

Even with the addition of a new category IV coating, the coating breakdown factor for DNV-RP-B401 is more conservative than the observations made in the 2015 Knudsen paper (Lønvik et al., 2019). The workshop stressed that the DNV-RP-B401 provides these coating breakdown factors as a very conservative back-up to be used in the absence of any field data or observations from the designer. The coating breakdown factors are intended to be conservative.

It is also relevant to note that the coating breakdown factors observed in the Knudsen et al study were for jacket structures built in the 1990s for oil and gas platforms (Knudsen and Olsen, 2015). We have not identified any work related to the coating breakdown factors inside of offshore wind monopiles. Since the internal corrosion issue was identified in 2011, it is unlikely that there are many field installations with internal coatings over 10 years old. In the absence of available data, it would seem safe to assume that the coating breakdown factors for coatings inside of monopiles would be lower than the coating breakdown factors for jackets in DNV-RP-B401 because the monopile interior is more sheltered. This is on top of the inherent conservativity to the B401 coating breakdown factors. These coating breakdown factors are very conservative by design and according to discussions in the workshop it is common practice to replace them if the designer has available field data that is appropriate.

3.2.5 Role of the Biology Microbes

Microbially influenced corrosion (MIC) is a type of corrosion which occurs on metal surfaces due to microbiological activity. The microorganisms settle on steel surfaces and form complex heterogenous communities which create a nonuniform microenvironment on the surface by yielding acidity, oxygenation, and altering the diffusivity of metabolites and nutrients. The growing microorganisms, i.e.

sulfate-reducing bacteria (SRB), corrode metal by consuming electrons to reduce the sulfate ions to H₂S (Revie, 2011).

The factors that affect the corrosion by biofilms are as follows (Revie, 2011).

- Direct effect on cathodic and anodic reactions.
- Microbial metabolites and exopolymetric changing the surface film resistivity.
- Creating microenvironments that enhance corrosion by lowering oxygen and increasing acidity.
- Forming concentration cells.

MIC may be prevented by utilizing CP systems, coatings, or a combination of both. Steel surfaces need to be polarized to potentials more negative than -0.9 V (ref. to Ag/AgCl/seawater) in an anaerobic environment with the risk of MIC (VGB PowerTech, 2018d). However, the relative importance of MIC is sometimes debated. For example, (Jansen et al., 2017) reported that the CP of a clean steel surface would mitigate MIC by increasing the surface pH, however, it wouldn't alter the surface pH and be effective to mitigate MIC if the microbiological community has already established on the surface. In another paper, a group looked at microbiologically influenced corrosion (MIC) under CP conditions both in lab settings and in the field (de Romero et al., 2008). In the lab, testing with the sulfate reducing bacteria *Desulfovibrio Desulfuricans*, found that because of the biofilm over the steel corrosion could occur under polarization of -1000 mV. In field observations made on pipelines in Lake Maracaibo, Venezuela, corrosion was observed in areas where cathodic polarization was over -900 mV (de Romero et al., 2008). There is no concrete evidence of MIC occurring in an offshore wind monopile, but it was flagged as a potential concern in 2013 because of the conditions in the mud zone and the risk of differential aeration (i.e. different oxygen levels near the mud line) (Hilbert et al., 2013). The Hilbert

paper concludes that documentation of the mud zone and an evaluation of these risks would be desirable; however, there does not appear to be any follow-up papers that focus on this issue. MIC remains a potential concern but is not currently a major focus for the industry.

3.2.6 Use of Perforations

Again, it is important to reiterate that the current practices for perforation design have not made it into the research literature, so this section relies heavily on workshop discussions. The main goal of the current practice is to minimize the structural impact of the holes by keeping the number and size of holes to a minimum. As few as four holes can be enough to provide sufficient water replenishment. Two of these holes can be placed 180 degrees to each other on the can below the tidal zone. The other two are typically a few meters above the seabed and rotated 90 degrees in reference to the top holes. The water replenishment holes are usually an elliptical shape under 1 m high and about 0.5 m wide. This is just a very rough approximation of what can be done for water replenishment. The actual design needs to consider site specific metocean data to ensure there is sufficient water circulation/replenishment.

Air exchange holes are also necessary to vent the dangerous gases generated by the CP systems and enable water movement within the column. There are both active and passive air ventilation systems that are currently in use. Active systems force air to leave the monopile and fill it with fresh air by fans, whereas passive systems rely on the vertical movement of the water column inside the monopile to move the air inside. Both systems typically have holes above the mean water line and below the air-tight platform. During the workshop, there was some discussion about passive vs active ventilation systems. There were no firm conclusions made, but some participants highlighted that putting any active system on these platforms does create a risk that it might fail and need to be repaired. Because these platforms are offshore, any repair activities would be particularly expensive. Currently,

there is little to no information about ventilation for monopiles systems in the literature or design practice documents.

The acceptable pH level of the enclosed water inside the monopiles is around pH 6-5.5 due to the sensitive materials, such as cable shields. Therefore, if the CP system is designed with aluminum anodes, water replenishment is required through perforations, whereas when zinc anodes are used, the acidification of the enclosed water is not a concern. Thus, replenishment holes are not required.

Finally, the introduction of perforations also introduces new design challenges for the platform. For example, the holes below the waterline allow a percentage of the wave height to travel through the internal water surface. The movement of the internal water surface acts like a piston and can create a significant uplifting force below the airtight platform if there are not enough ventilation holes to allow the air to escape. The holes can also create water jets depending on the wave conditions. This high-water velocity could affect equipment inside of the monopile such as the hanging anodes. The ability to research these questions is particularly limited by the lack of published information on perforations.

3.3 Future Potential

While there has been a significant level of work done on internal monopile corrosion and the relationship with water replenishment and circulation, there are still several questions and areas for refinement.

3.3.1 Identification of Ideal Corrosion Protection Systems

As discussed in section 2, there are a wide variety of systems being used for corrosion protection inside of monopiles. This situation with a design envelope containing many viable options is not an uncommon feature of offshore wind substructure design. For example, there are multiple options used in the industry for foundation type selection for fixed offshore wind (i.e., monopile, concrete gravity

base, or jacket). However, for selection of foundation type, there is information available about how different selections are related to important variables such as water depth, geographic region, distance to coast, and turbine hub height (Sánchez et al., 2019). These relationships are not set rules, but they are useful guidelines for preliminary designs and give new designers or policy makers a place to start when understanding the industry.

An equivalent analysis to the Sanchez et al work has not been done for different internal corrosion protection systems. There are multiple potential reasons for this case. For example, corrosion protection systems were historically viewed as a niche field by the industry and not necessarily given a lot of focus (Wyatt et al., 2020). Also, the longest performing internal corrosion protection systems are going to be the retrofits of the early monopiles. These retrofits also make up the bulk of the research literature. The constraints for these retrofits are going to be different than corrosion protection systems designed alongside the structural design. Internal corrosion protection systems designed according to the best practices are likely to be approaching ten years old today because the research literature on internal water acidification for aluminum other field observations only entered the literature around 2015. There will not be much field data on internal corrosion protection system performance available until these systems are inspected.

A better understanding of design variables impacting internal corrosion protection system selection is also important because the current options in use have distinct advantages and disadvantages. For example, a zinc or aluminum system may be controlled by the anode mass required to provide enough current for the whole 20–30-year lifespan of the monopile. This would make these systems more sensitive to coating selection decisions or the distance to shore. If a design wants to use an unperforated pile to take advantage of a semi-sealed system with some oxygen ingress, it may be sensitive to the diameter of the pile and size of the internal water column. Additionally, perforation designs and patterns are inherently going to be sensitive to metocean conditions to drive the water

circulation as well as the local ecosystem and biofouling species that could occlude the holes. Finally, ICCP systems would need to be built in a very robust way to avoid expensive maintenance activities and system reliability would be a critical variable. While the individual case studies in the literature are useful, from a feasibility perspective, the bigger picture of system reliability across hundreds of structures is missing.

3.3.2 Opportunities for Corrosion Monitoring

One of the keys to better understanding the long-term performance of these systems is going to be corrosion monitoring. However, there is no pre-existing documentation or best practice guidance for corrosion monitoring systems (NGI, 2017). As a result, even when data is collected, the quantity and quality of data varies wildly from farm to farm, making comparisons difficult. Because corrosion monitoring is still in its earlier stages of development and is not firmly established, it is important to get an idea for how the industry views the opportunity.

An industry survey contained within the Interreg CIG Report on corrosion monitoring provides helpful insight into how the industry views corrosion monitoring for ocean energy devices in general. Figure 21 from their survey results show that optimization of operation and maintenance activities is a key goal for corrosion monitoring with remaining life prediction, and R&D also getting a majority selection (Tacq, 2021). This is especially relevant in the context of another one of their findings that 27 out of 30 respondents said they did not have a clear view on how the capital (CAPEX) costs of protecting against corrosion related to the maintenance costs of corrosion (OPEX) for ocean energy devices (Tacq, 2021). In the context of O&M optimization, all the respondents believed corrosion monitoring could help reduce OPEX but there was not a clear picture about how much value it could provide (Tacq, 2021).

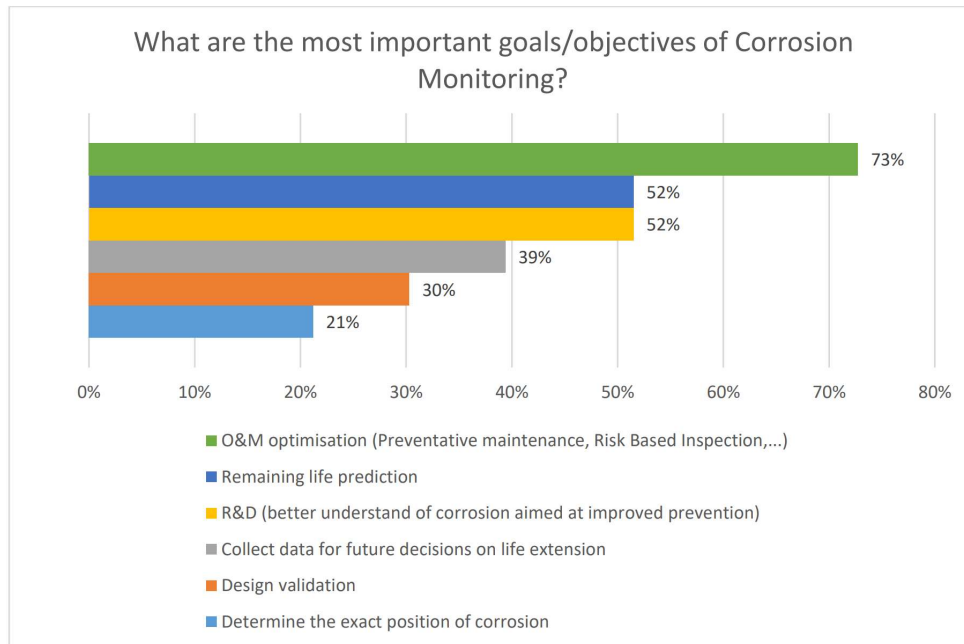


Figure 21 Interreg CIG Report Survey Results Goals of Monitoring Reproduced from Tacq Report

One of the major reasons why there may be uncertainty about the benefits of corrosion monitoring is that there is not a clear understanding of how to do corrosion monitoring effectively. In Figure 22 the respondents' most common concern was an uncertainty about what sensors to use in a maritime environment, and the third most common concern was about what parameters to measure. The Interreg survey focused on this issue directly by asking what variables matter for corrosion monitoring in Figure 23 (Tacq, 2021). A similar question was asked in the postworkshop survey by our team, seen in Figure 24. There is some disagreement with the two survey results. Figure 23 is more concerned with the direct results of the corrosion (i.e., CP efficacy, loss of wall thickness, coating degradation, and pitting corrosion) while environmental variables such as water quality and H₂S generation are much less commonly selected. Figure 24 was focused more on the environmental variables and while direct measurement of corrosion rates was the most common selection, environmental variables such as pH and dissolved oxygen measurements were identified as important. Part of this difference is due to the survey design and the fact that the focus of Figure 24 is specifically on

internal corrosion monitoring for monopiles while Figure 23 is geared towards corrosion monitoring in all cases for offshore energy devices.

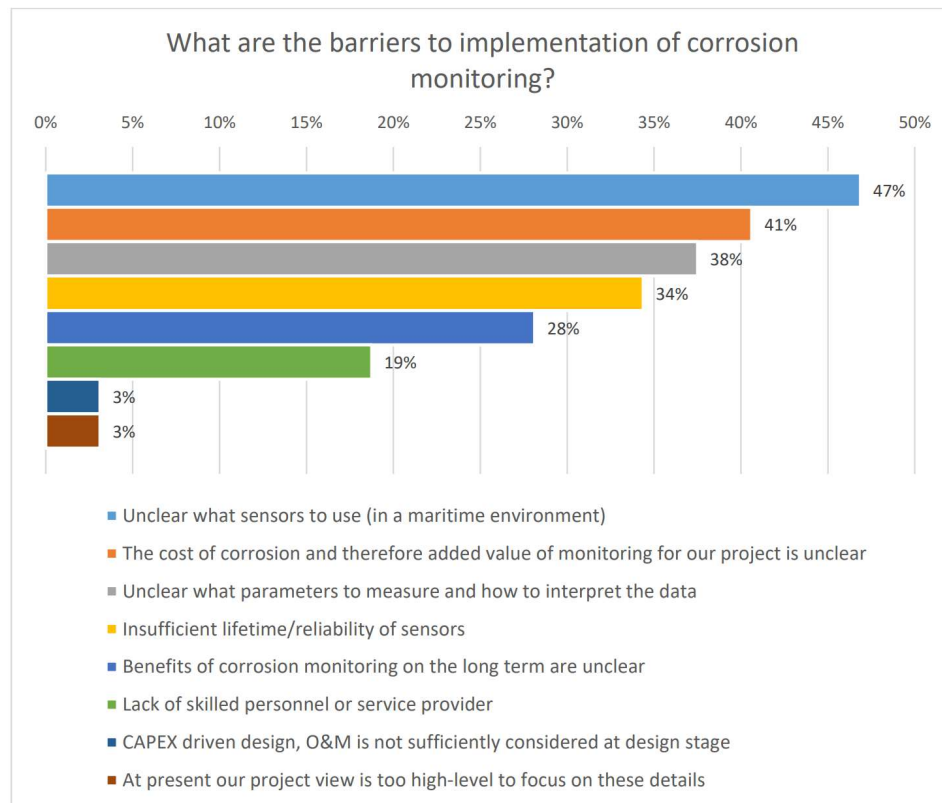


Figure 22 Interreg CIG Report Survey Results Barriers to Monitoring Reproduced with Permission from
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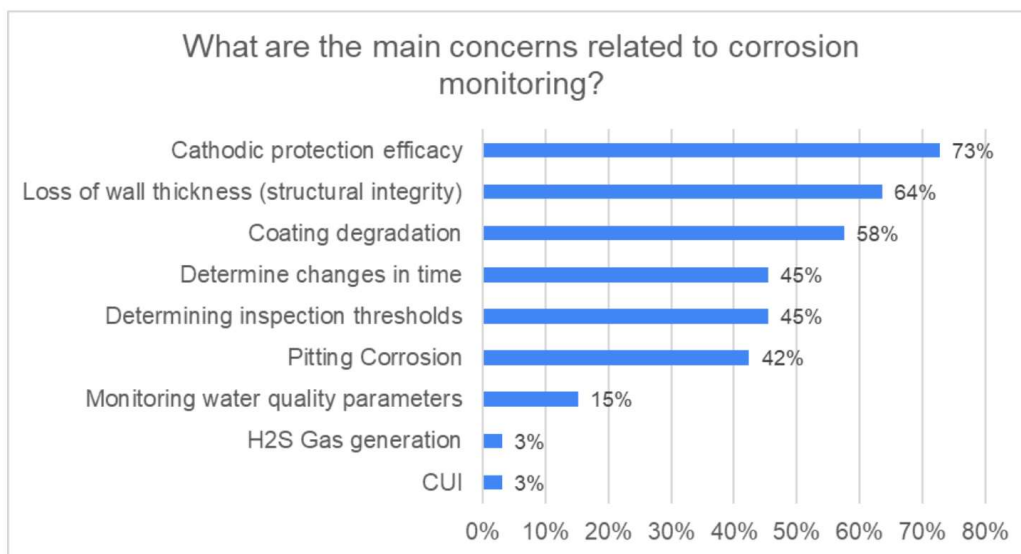


Figure 23 Interreg CIG Report Survey Results Main Concerns for Corrosion Monitoring Reproduced with Permission from Report Author

4.) Please select the environmental variables you think would provide the most valuable information about risk of corrosion occurring inside of the monopile. Please try and limit your response to the top 3 unless you are certain more variables are needed.

12 responses

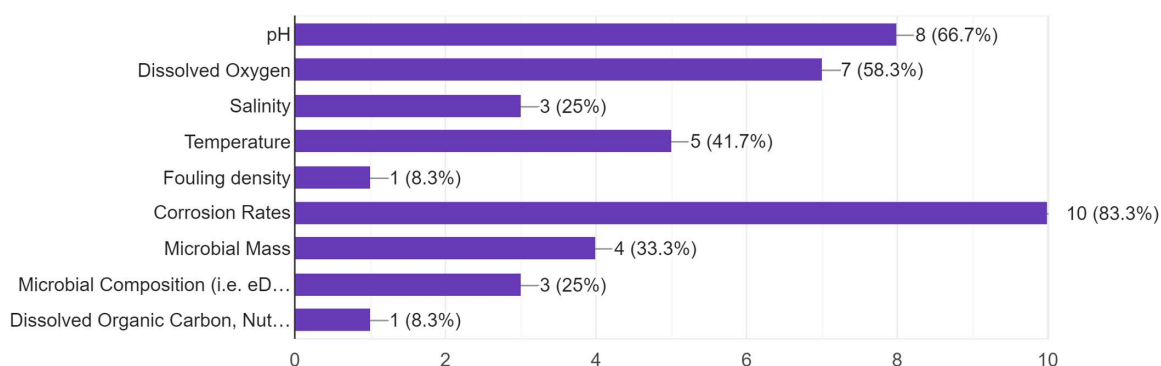


Figure 24 Postworkshop survey results about key variables to monitor internal corrosion

While there are not any specific recommended practices or standards available for offshore wind monopile corrosion monitoring, several research projects have utilized corrosion monitoring. Much of

the initial experience in corrosion monitoring for monopiles comes from studying the corrosion conditions inside of the early monopile retrofits (Nøhr-Nielsen, 2018). In general, five common techniques were identified for internal corrosion monitoring in a 2018 review of corrosion monitoring techniques (Nøhr-Nielsen, 2018):

1. Corrosion coupons spread out across the water column and in the different zones (i.e., submerged, intertidal, and atmospheric)
2. Full length corrosion coupon to capture macro-cell effects along the whole water column including the beginning of the mud zone.
3. Electrical resistance (ER) probes for measuring the corrosion rates
4. Magnet mounted reference electrodes for measurement of cathodic system potential
5. Lowerable racks of sensors to measure potential, pH, dissolved oxygen, and resistivity

These are common and well-established methods for monitoring corrosion. For example, Mathiesen et al used a combination of UT crawlers, coupons, er probes, and visual inspection in their study (Mathiesen et al., 2016). Corrosion coupons have also been used extensively, and recent work has even focused on scanning field coupons to better understand how corrosion impacts the surface of the steel coupon and better connect corrosion damage to fatigue life (Khodabux et al., 2021). In addition to these more well-established methods of corrosion monitoring, the iWindCr project from innovate UK was identified as a new corrosion monitoring method focused on using a low power wireless sensor system to monitor corrosion rates (Ahuir-Torres et al., 2019). The iWindCr project is in early stages but has recently been tested in the field in the external splash zone (Simandjuntak et al., 2021). Work is also being done to use underwater imaging to measure corrosion area and damage based on images captured from remote operated vehicles (ROVs) (Tacq, 2021). This imaging technology is currently being

tested and is at a TRL of about 5-6 (Tacq, 2021). At this time there are many different options available for corrosion monitoring, but this information needs to be transferred to practical use by the industry. A key missing piece is a recommended practice or regulatory guidance document that could set a standard baseline for these kinds of systems. While no widely applicable standards currently exist for these systems in offshore wind Brijder in their review article goes over multiple difference technologies in development with a focus on highlighting non-destructive systems that can be combined with corrosion modeling to create hybrid monitoring systems (Brijder et al., 2022).

3.3.3 Potential for Perforations Designed for Additional Effects

Perforating the monopiles to improve the performance of the CP systems opens the potential to perforate for other reasons as well. First, opening the monopile via perforations has the potential to introduce more surface area for species colonization and could affect the impact of the monopiles on the local environment. Furthermore, there has been research into the effects of perforations on wave loads to help monopiles designs extend into deeper waters.

It is difficult to describe the relationship between perforated monopiles and the environment because there is currently no field data available in the literature describing what grows inside of a perforated monopile. However there has been field testing done in Florida on small scale pipes designed to simulate perforated monopiles (Maher and Swain, 2019). Figure 25 shows four different pipes after 8 weeks immersed in a dockside study in Florida (Maher, 2018). It is clear to see that the perforated pipes contained a much greater level of biological life than the unperforated pipes. A follow up to this initial work was published in 2024 that found no difference in interior recruitment between pipes with sacrificial anodes and impressed current systems (Paluzzi et al., 2024). However, this follows work from Paluzzi that observed a noticeable decrease in overall species recruitment inside of the pipes despite the

study occurring in the same location and time of year. This emphasizes the challenges of marine recruitment studies and the variability of bio-colonization.



Figure 25 Images of biofouling within perforated vs unperforated pipes. Reproduced with permission

In addition to the work associated with perforations and the environment, work has also been done about the potential of perforations to reduce wave loading on monopiles. These perforation designs remove much more of the surface area of the monopile than the corrosion protection holes designed specifically to minimize structural impact. The first written evidence of this idea for offshore wind comes from a patent in 2020 that proposed a perforation pattern to reduce wave loads on the monopile (Baun and Neubauer, 2020). This perforation pattern was tested in a wave tank in 2020, and a reduction in wave loads associated with the fatigue life of a structure was measured (Andersen et al., 2020). This work was continued in a 2021 master's thesis that calculated the change in fatigue life using this perforation pattern, and they found that the perforations had a meaningful change in fatigue life of the structure (van der Ploeg, 2021).

The ability to design perforated monopiles for these other use cases is directly tied to the understanding of how these internal corrosion protection systems perform and therefore is tied to a robust monitoring program. For example, if there is significant biological life within the monopile, it is important to understand how this impacts the internal water chemistry such as dissolved oxygen. It is possible that a change in environment could increase the risk of microbiologically influenced corrosion MIC. Another possibility is that if a greater number of perforations are used to reduce the wave loading, it may change the flow of water in and out of the perforated monopile. If this change resulted in the water column stratifying with pockets of stagnant water not being replenished near the mudline, this could impact the performance of the corrosion protection system. Because these ideas are still theoretical, the effects and potential of perforations beyond the CP system are not well understood.

3.3.4 Test beds

From the perspective of corrosion monitoring and biological tracking, there is a real opportunity for the fixed offshore wind industry to pioneer technologies useful to the larger “blue economy.” For example, in 2018 the North Sea Solutions for Innovation in Corrosion for Energy project (NeSSIE) completed a report on the economic opportunity for corrosion management systems including corrosion protection, corrosion monitoring, and biofouling measurement (Laurie and van Velzen, 2018). In this report, specific technological needs were identified for various kinds of offshore renewable energy. For marine energy (i.e., wave and tidal) the report highlights biofouling monitoring and corrosion monitoring systems as major areas for technological development. For floating offshore wind, they highlight that one of the benefits of floating offshore wind is the ability to build in deeper waters further from shore, but this greater distance makes inspection and maintenance activities in the field more expensive (Laurie and van Velzen, 2018). These capabilities of biofouling monitoring, corrosion monitoring, and remote sensing could also be useful for fixed offshore wind platforms. For example, one significant concern for

offshore wind platforms is the potential for them to be colonized by invasive species (Horwath et al., 2021). This concern could be tracked via some form of biofouling monitoring to help manage the risk. One of the key trends identified in the report is growth across sectors using oil and gas and offshore wind as examples (Laurie and van Velzen, 2018). The fixed offshore wind industry is in a position where it can drive the supply chains and uses for technologies such as remote corrosion monitoring that can then be applied in young sectors like floating offshore wind and even nascent sectors like marine energy.

In addition to fixed offshore wind's position to pioneer new monitoring technologies and strategies, there is also potential to co-locate offshore wind farms with other ocean activities such as fisheries and aquaculture. In 2017, one of the case studies examined by the Multi-Use in European Seas (MUSES) project looked at the potential for combining offshore wind farms with marine fisheries and aquaculture in the German (EEZ) part of the North Sea (Schupp and Buck, 2017). After reviewing the potential from economic, environmental, and legal perspective the MUSES authors found that combining fisheries with wind energy areas was closer to realization than combining aquaculture with wind energy areas, but aquaculture remained promising (Schupp and Buck, 2017). In another example, (van den Burg et al., 2020) created a framework to examine the risk associated with combining seaweed aquaculture and offshore wind farms after a literature review and workshop with 30 experts in the field. Finally, (Huang et al., 2022) examined the economic feasibility of cage aquaculture in offshore wind farms in Taiwan. This research was done to restore fishery resources in the wind energy areas. While these projects are not a comprehensive review of all the co-location efforts in the literature, they do show that there is a significant interest in better utilizing the ocean space of the wind energy areas. However, this work requires a deep understanding of the biology associated with the offshore wind foundation structural design details such as perforations.

3.4 Conclusion and Key Findings

The story of corrosion inside of offshore wind monopiles can be viewed from two perspectives the technical and the big picture. There are important technical lessons regarding anode selection, water replenishment, and coating performance; there are also big picture lessons about how information disseminates in a young industry, the importance of communication between disciplines in the design marine structures, and the potential for perforations to play a larger role in monopile design and the interaction with the local biology.

Key Findings:

- There are a variety of viable options for internal corrosion protection systems used in the industry. Not enough information is available about their long-term performance to definitively say which is the most cost-effective option for different scenarios.
- The three main categories of internal corrosion protection are:
 - Internal coating, unperforated, with no CP
 - Internal coating, unperforated with zinc CP
 - Internal coating, perforated, with ICCP (maybe aluminum as well)
- Perforations in the monopile are a popular choice of internal corrosion protection systems even though they are not well represented in the literature.
- For an aluminum anode system water replenishment is critical to avoid large drops in pH. A water replenishment rate of around 10% per day is commonly found in the literature.
- For an impressed current system, perforations are important to maintain the pH and to ventilate dangerous gases such as chlorine.

- The technology to monitor corrosion exists but has not been formally put into practice in a systematic way throughout the industry.
- There is an opportunity to incorporate the environmental impact of perforations into the design process of the monopile, potentially for ecosystem enhancement.
- In a young industry, there are wide gaps between what the industry knows, what is in the published literature, and what is in design guidance documents. Because of these disparities, the expertise of the corrosion protection designer is critical to the long-term performance of the corrosion protection system. This is a critical point to remember for stakeholders with oversight obligations such as regulators.
- Marine structure design is a highly interdisciplinary field. One small design decision, like perforations, can interact with the corrosion protection system, structural design, and the biological impacts of a structure.
- Information can become siloed within disciplines. This is particularly important as the industry moves into new markets and the technical workforce expands. To counter this risk, it is important to survey the industry experts and ideally gather interdisciplinary teams to identify gaps in the available literature.
- There is significant interest in combining wind energy areas with aquaculture across the larger blue economy. This will require a deeper understanding of the environmental impacts of monopiles. It is possible that perforated monopiles may interact with the environment differently than unperforated monopiles.

As the industry develops, more data and analysis can be completed on the long-term performance of these offshore wind monopiles. This includes the performance of the structural steel,

corrosion protection system, and interactions with the environment. Each of these is a key pillar to the overall impact of the monopile. Perforations are a good example of an aspect of monopile design that touches all three pillars and requires an interdisciplinary framework to analyze. This interdisciplinary spirit needs to be the future of the offshore wind industry.

Primary Contributions of PhD Research

The history of corrosion issues inside of monopiles had not been previously compiled beyond conference papers on individual topics. Requirements from design documents and industry insights were analyzed to understand the interaction of corrosion protection methods, fatigue design, and holistic foundation design. Based on this, new insights were made into how to design suitably robust internal corrosion protection systems.

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Chapter 4 Corrosion-Fatigue Capacity Testing

As established in Chapters 2 and 3, corrosion can be a major risk for offshore wind support structures. This makes the phenomenon of corrosion-fatigue very important. This chapter analyzes the testing corrosion-fatigue testing that has been done to understand the corrosion-fatigue capacity of mild carbon steel. The first section focuses on LEFM testing that provides insight into crack growth rates. The second section focuses on corrosion-fatigue SN curve testing that covers the entirety of corrosion-fatigue life. This analysis was done to highlight the limitations and uncertainties inherent to existing corrosion fatigue testing and establish a baseline for how the corrosion-fatigue damage models were established before they are applied in Chapter 5 on actual offshore wind support structure data.

4.1 Summary of Corrosion Effects from LEFM Testing

Corrosion-fatigue damage is affected by loading, environmental conditions, and material properties. These three variables interact and complicate the corrosion-fatigue process. Before examining the test data used to generate S-N curves, it is necessary to understand the variables that affect the results of a corrosion-fatigue test.

Because there are several variables that affect corrosion-fatigue damage accumulation, no single study or research team has compared all variables comprehensively. It is necessary to draw from a variety of studies and papers to comment on the effects of multiple variables. Some of these studies are from the 1970s and 1980s, when manufacturing methods and materials were much different than modern standards. While these early corrosion-fatigue tests will be referenced, the greatest weight has been given to the most recent testing from the Structural Lifecycle Industrial Collaboration (SLIC) project that concluded in 2020 (Adedipe et al., 2015, 2017; Adedipe et al., 2016; Brennan, Kolios, & Tavares,

2017; Brennan & Tavares, 2014; Consortium, 2019; Igwemezie et al., 2018; Mehmanparast, Taylor, Brennan, & Tavares, 2018; Mehmanparast, Brennan, & Tavares, 2017).

This discussion about loading, environmental, and material effects comes from LEFM testing. There has been little research into the effects of environmental variables on crack initiation and SN testing. Fracture mechanics tests are historically the most common test for corrosion-fatigue damage because they are faster to run. Not all the relationships will be summarized in detail, and the reader may be directed to relevant technical papers and reports for additional information.

4.1.1 Loading Effects on Corrosion-fatigue

For decades, it was known that loading conditions have a significant impact on the corrosion-fatigue crack growth rate. One major study from the oil and gas industry in the 1980s found that corrosion-fatigue crack propagation was sensitive to frequency, waveshape, and stress ratio (Scott, Thorpe, Silvester, Division, & Oxi, 1983). In addition to oil and gas industry testing, this section will focus on the SLIC project. Waveshape has been excluded from the comparison of relevant variables because modern testing appears to agree on the use of a sinusoidal waveshape for testing.

Frequency Effects

It is well known that frequency influences corrosion-fatigue crack growth rates. For example, testing done by Wei and Simmons on high-strength steels in water vapor showed a clear relationship between frequency and crack growth (Wei & Simmons, 1981). Figure 26 shows that in their testing lower loading frequency leads to faster corrosion-fatigue crack growth rates.

The same relationship was found in the Scott and Thorpe testing on a mild steel, BS 4360:50D, which is similar to the modern S355 steel used in monopiles (Thorpe, Scott, Rance, & Silvester, 1983). This testing was done in simulated seawater with cathodic protection rather than water vapor. The

Thorpe et al. paper was cited by a review article from Adedipe et al. on corrosion-fatigue that also identified this trend (Adedipe, Brennan, & Kolios, 2016). Figure 27, from the Adedipe et al review, shows on a loglog scale that as the frequency decreases, the crack growth rate increases.

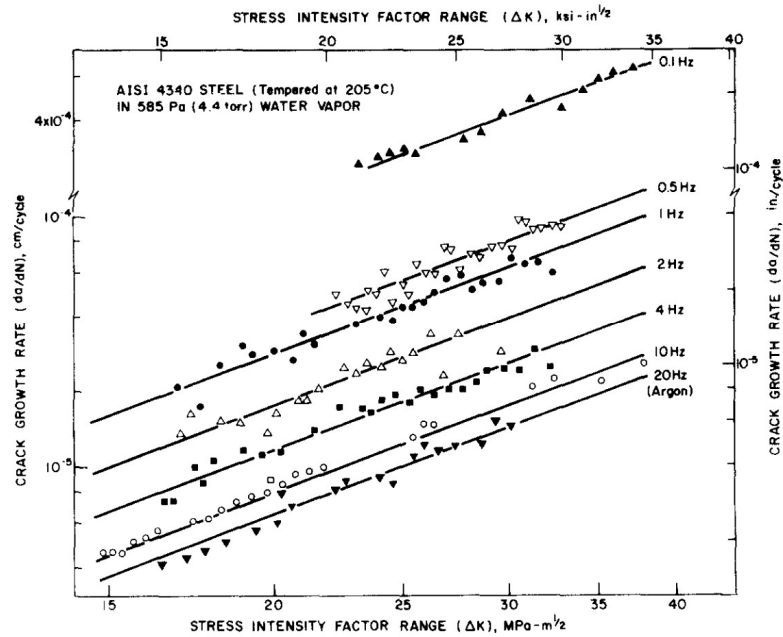


Figure 26. Frequency effect on corrosion-fatigue crack growth rates (from Wei 1981)

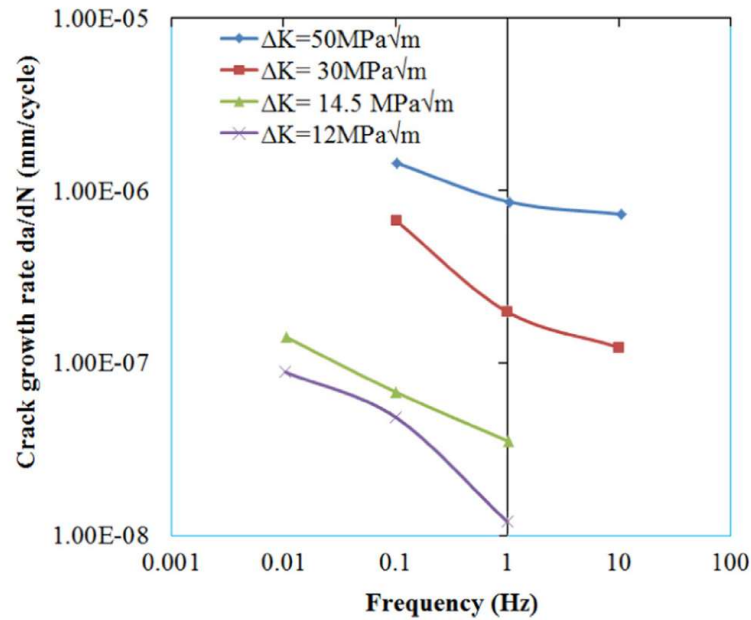


Figure 27. Frequency effect on corrosion-fatigue crack growth rates (from Adedipe 2016)

The SLIC project also tested the effect of loading frequency on modern specimens of s355 steel under free corrosion conditions and the results of this test can be seen in Figure 28 and Figure 29 (Adedipe, Brennan, & Kolios, 2015). The 0.40 Hz test and the 0.35 Hz test are the only tests that directly compare the frequency effect, because the 0.3 Hz test used a different loading ratio than the 0.4 Hz and 0.35 Hz test. Figure 28 shows the Paris Plot of Δk vs crack growth rate, while Figure 29 plots the number of cycles vs crack length (Adedipe et al., 2015). Figure 29 shows that the frequency effect is not noticeable until about 30% of the way through the test. The effect is more difficult to notice in the Paris plot, but in Figure 29 the 0.35 Hz test diverges from the 0.4 Hz test just before 1,000,000 cycles. In their analysis, the SLIC team found that for higher Δk , the crack growth rate for the 0.35 Hz test was double that of 0.40 Hz. Because the Paris plot is a log-log scale, the small visual difference in Figure 28 causes the significant difference seen in Figure 29.

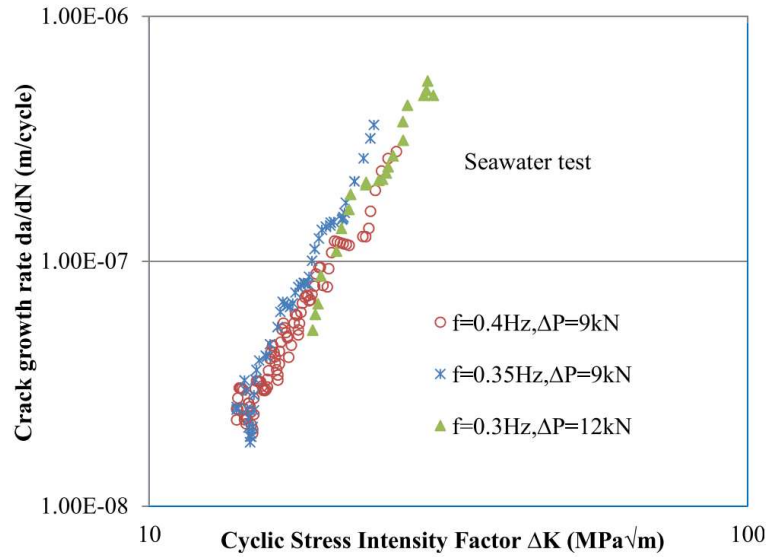


Figure 28. Paris plot for crack growth rates frequency comparison (from Adedipe 2015)

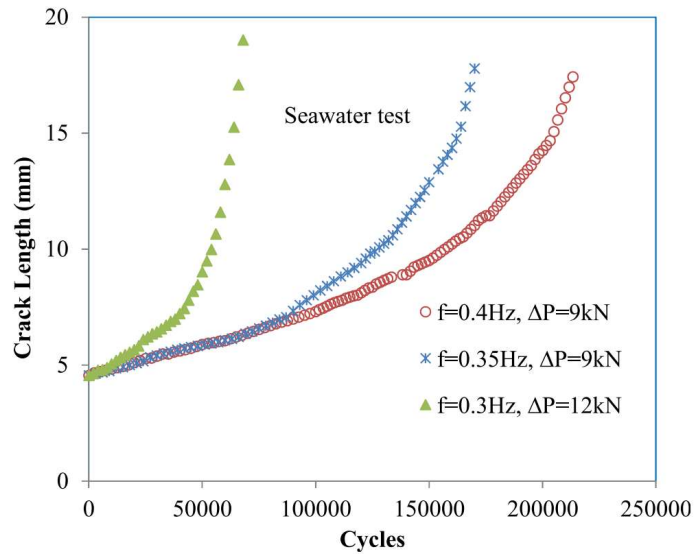


Figure 29. Crack length over number of cycles frequency comparison (from Adedipe 2015)

Mean Stress and Loading Ratio

The load ratio, defined as $r = \frac{\sigma_{min}}{\sigma_{max}}$, is often used as a measure of the mean stress for corrosion-fatigue tests. Some of the earliest research about the effects of load ratio on corrosion-fatigue crack growth rates comes from (Thorpe et al., 1983). Figure 30 from the Thorpe study was redrawn in the

Adedipe review paper (Adedipe et al., 2016). Figure 30 shows that the load ratio effect is much greater for seawater testing, on the right, than the in-air testing, on the left.

This test was done on BS 4360:50D steel at a loading frequency of 0.1 Hz under free corrosion potential conditions. Free corrosion potential represents a metal with an electropotential of $-0.65V$ (Ag/Cl). As the load ratio increases, the crack growth rate also increases.

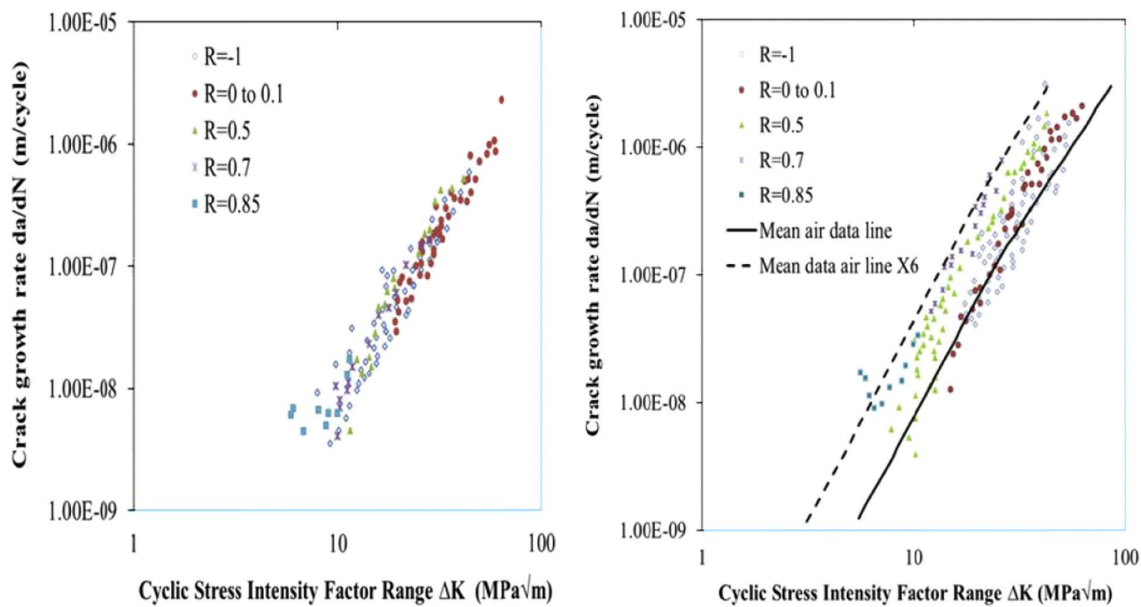


Figure 30. Comparison of load ratio effects for in-air conditions (left) and seawater conditions (right), redrawn from Adedipe (2016)

Figure 31 from the SLIC project shows that as the load ratio increases, the corrosion-fatigue crack growth rate also increases (Adedipe, Brennan, Mehmanparast, Kolios, & Tavares, 2017). The SLIC project team found that under free corrosion conditions, the effect of the load ratio was greatest at lower/mid-range ΔK values. This is attributed to corrosion products blocking access to the crack tip, which reduces the rate of corrosion as the test progresses. This idea matches the relationship between crack closure effects and the stress ratio detailed in (Burnside, Hudak, Oelkers, Chan, & Dexter, 1984).

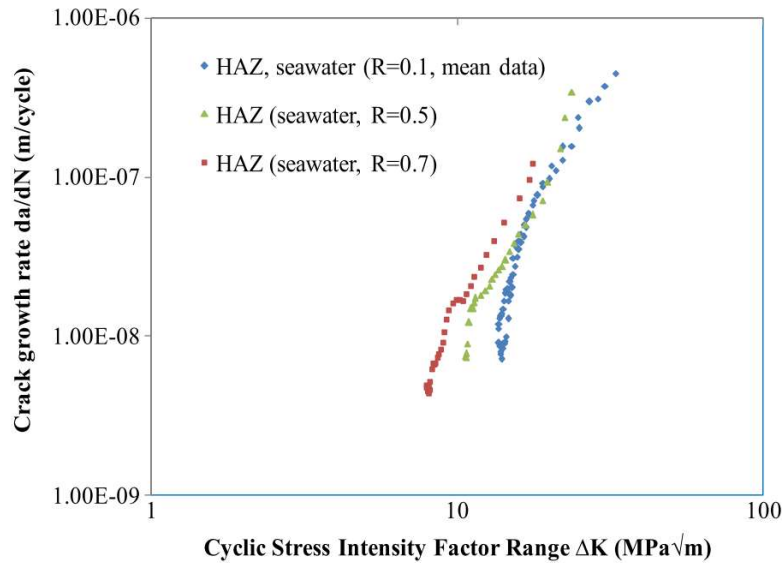


Figure 31. Load ratio effect under free corrosion conditions from SLIC project (Adedipe 2017)

Research into the effect of loading ratio is particularly important because of the impact of residual stress on large scale welds. The manufacturing process of offshore wind monopiles can introduce significant residual stresses via the rolling of the flat plates into cans and the circumferential welding of the cans into piles. The residual stresses mean that steel monopiles can experience a high loading ratio even if the magnitude of external loadings is relatively small. One study from Rikken et al. describes the residual stresses that welding can introduce to steel (Rikken, Pijpers, Slot, & Maljaars, 2018). The paper was designed to find a method that predicts the residual stress caused by a weld by incorporating phase transformations and volumetric strains. Figure 32 shows the weld used in testing and the differences in temperature introduced in the welding process (Rikken et al., 2018). Figure 33 shows the distribution of residual stresses through the thickness of the plate 2 millimeters from the weld toe (Rikken et al., 2018). Residual stresses are especially important for thick plates, such as those used in monopile foundations.

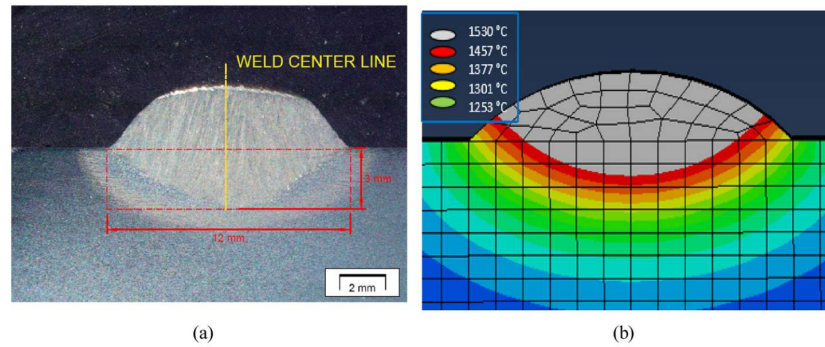


Figure 32. Heat distribution in a weld (Rikken 2018)

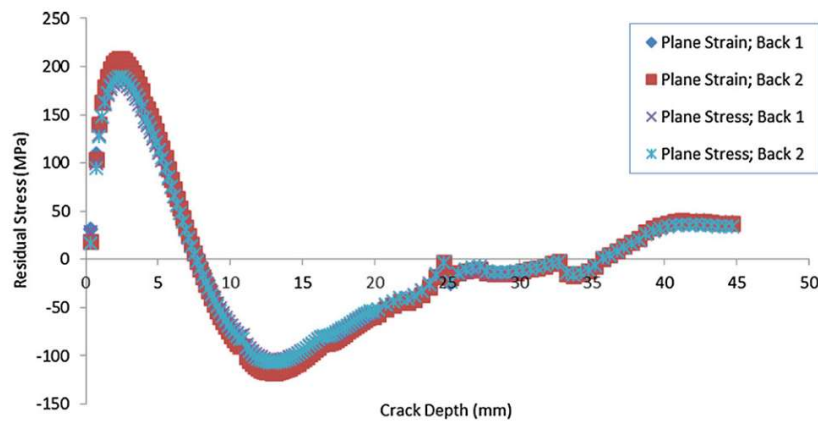


Figure 33. Residual Stresses from a bead on plate weld 2 mm from weld toe (from Rikken, 2018)

Load Sequencing

One challenge with fatigue analysis is that the distribution of load cycles is often not time dependent. After a time series of stresses is run through a rainflow cycle counting algorithm the sequence information is lost. Assuming the load sequencing does not matter adds uncertainty to the analysis. According to BSI-7910 (2015) using a fracture mechanics suggests that under variable amplitude loading it may “overestimate fatigue life and for critical conditions the calculated fatigue life should be halved” (BSI, 2015).

In the literature, a study from Ziegler compared an S-N curve analysis with a calibrated LEFM analysis studied the effect of seasonality on a calibrated FM model using a Markov weather model and

Monte Carlo simulations (Ziegler & Muskulus, 2016). Their analysis showed that the persistent weather, a.k.a. the Markov weather model used to study seasonality, has a much larger standard deviation for potential final crack depth than the random weather model.

The effects of overloading and underloading may be what drives the effect observed by Ziegler & Muskulus. Overloads and underloads represent uncharacteristically high or low loads (Maljaars, Pijpers, & Slot, 2015). The high peak stresses in uncharacteristic overloads can create plastic deformations that cause subsequent loads to cause less fatigue damage. Figure 34 illustrates some of the proposed mechanisms for how overloading retards crack growth. More details on these mechanisms are presented in the Maljaars paper.

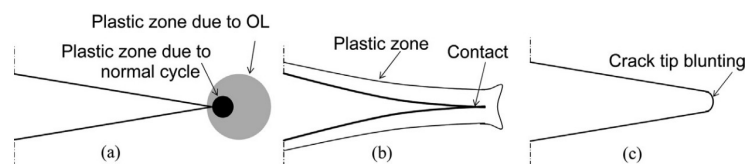


Figure 34. Diagram of the overloading effect (from Maljaars 2015)

Underloading, the occurrence of an uncharacteristically low load, is not as well studied or understood (Maljaars et al., 2015). However, underloading is believed to have an accelerating effect on the fatigue crack growth rate. Additionally, in most cases of variable amplitude loading, these effects usually balance out. This was determined to be the case for the effect of overloads when the model created in the 2015 study was applied to realistic loading data from a wind turbine and it was found that the overload and underload effects cancelled one another out (Dragt, Hengeveld, & Maljaars, 2018). Ultimately the impact of load sequencing on fatigue crack growth rates is an area of active research but none of this work accounts for the crack initiation phase. To better understand the effects on the total fatigue life the impact of variable amplitude loading on SN curve analysis will be examined in the next section.

4.1.2 Environmental Effects

Corrosion-fatigue testing is one part of a wider field named environmentally assisted cracking (EAC). Water chemistry, water temperature, microbiological life, and electropotentials (related to the cathodic protection system) have been identified as environmental factors that affect crack growth rates. It is important to recognize that although this chapter separates them, these variables are interconnected. For example, the water temperature will influence microbiological life, and microbiological life can produce waste that affects water chemistry.

Temperature

Temperature effects have not been a major focus for corrosion-fatigue research. For example, all the SLIC testing was done between 8°C and 10°C to simulate North Sea conditions. Thorpe et al. found that the corrosion-fatigue crack growth rate doubled when the temperature was raised from 5°C to 20°C (Thorpe et al., 1983). A review of corrosion-fatigue test data done by the Southwest Research Institute also found a positive correlation between rising water temperatures and faster corrosion-fatigue crack growth rates across various studies but it was not the same magnitude as Thorpe (Burnside et al., 1984).

The main method of relating water temperature to the corrosion-fatigue crack growth rate is the Arrhenius Equation. The Arrhenius Equation comes from chemistry and relates temperature to reaction rates, Equation 6. This relationship states that the crack growth rate at a certain temperature is proportional to $\frac{1}{T}$, where T is the temperature in Kelvin. $-E_{act}$ is a constant and represents the activation energy of the corrosion reaction. R_G is the gas constant, $8.3143 \text{ J} \cdot \text{K}^{-1} \cdot \text{mole}^{-1}$. Figure 35 shows a plot taken from a modern review paper that relates existing temperature data to crack growth rates (Jakubowski, 2017). The slope of the line of best fit through each dataset represents the activation energy of the corrosion reaction. It is also important to note that in this paper, the Scott/Thorpe data, labeled as Scott, is seen as an outlier. Furthermore, there is not a large body of test data to draw on for

temperature sensitivity analysis. The Arrhenius equation could be used to create a correction factor for water temperature in corrosion-fatigue testing or to explore the effects of offshore wind farms in warmer waters like the Gulf of Mexico in the US.

$$\frac{da}{dN_T} \propto \exp\left(\frac{-E_{act}}{R_G T}\right) \quad \text{Equation 6}$$

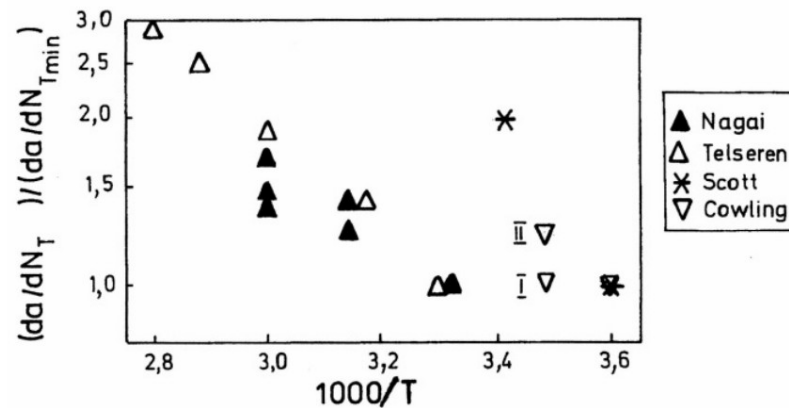


Figure 35. Arrhenius plot comparing corrosion-fatigue temperature relationships (from Jakubowski)

Both DNVGL-RP-C203 (2016) and BSI-7910 (2015) are limited in their consideration of temperature. DNVGL-RP-C203 (2016) has a correction factor for temperatures above 100°C for fatigue stresses, but does not mention the effect of temperature on the corrosion-fatigue interaction (DNV GL, 2016b). Meanwhile, BSI 7910 (2015) states that the given A and m constants for the Paris Equation are only applicable for temperatures up to 20°C (BSI, 2015).

Water Chemistry

Water chemistry can also impact corrosion rates and chemical products. Testing from Thorpe et al. found that the following changes in water chemistry had only second-order effects of the corrosion-fatigue crack growth rate (Thorpe et al., 1983). Another paper from Scott et al. studied the role of carbonate/bicarbonate buffer in how the cathodic protection increases fatigue life (Scott et al., 1983). This buffer precipitates due to the cathodic protection forming a protective scale on the steel. This scale

protects the steel during the crack growth phase due to crack closure effects. If the reader is interested in the chemical process that occurs in a growing crack tip, Gangloff's paper is a good source for further reading (Gangloff, 1985).

Cathodic Protection (CP)

Another major environmental effect is the electropotential of the metal related to the cathodic protection system, see chapter 2. DNVGL-RP-B401 (2011) "Cathodic Protection Design," suggests that a range of -0.9 V to -1.05 V (Ag/AgCl/seawater) is appropriate for a CP system and anything over -1.15 V is overprotected (DNV GL, 2017). The design of the CP system and electropotential of the steel is important, because in a CP system part of the cathodic reaction at the steel is hydrogen production. If the electropotential of the structural steel is too negative due to overprotection, the hydrogen produced at the cathode can lead to accelerated hydrogen embrittlement and increase the corrosion-fatigue crack growth rate. This phenomenon is studied extensively in (Burnside et al., 1984; Scott et al., 1983; Vosikovsky, 1975).

Figure 36 taken from Burnside et al. shows the relationship between crack propagation rate and the level of electropotential is parabolic. The minimum is around the range recommended by DNVGL-RP-B401 (DNV GL, 2017). It is also important to note that even under ideal cathodic protection, the corrosion-fatigue crack growth rate is still greater than the air conditions. This matches what is shown in the fatigue recommended practice, DNVGL-RP-203 (2016) with the cathodic protection curve.

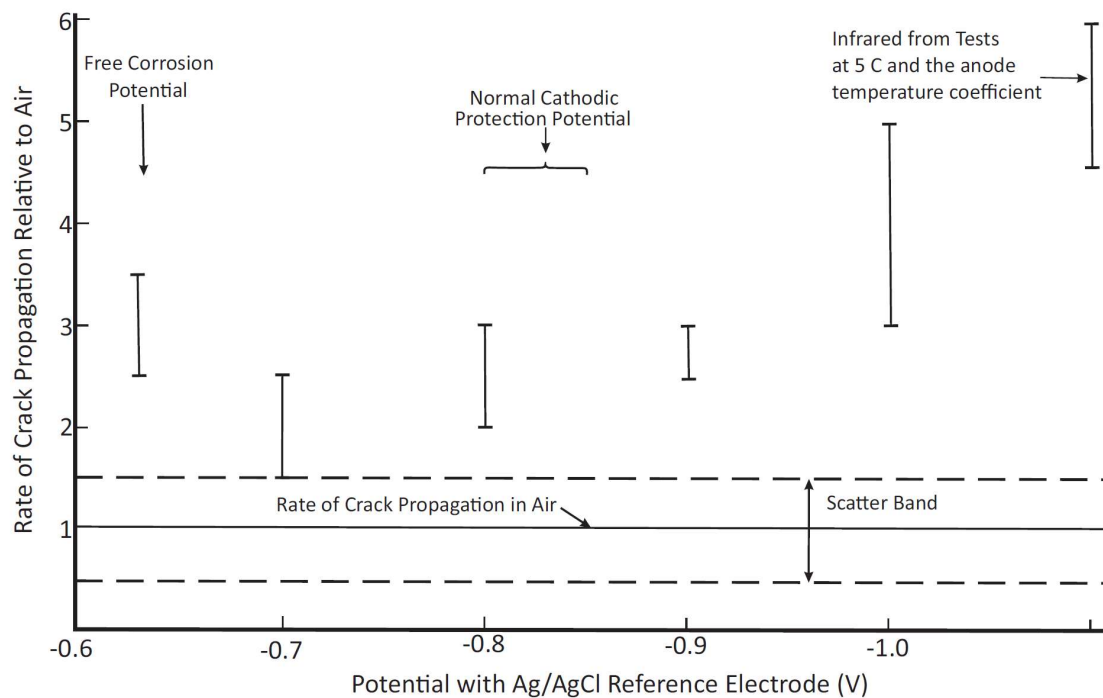


Figure 36. Electropotential and crack propagation rates (adapted from Burnside 1984)

Finally, electropotentials have been linked to the formation of biofilms and MIC. The study from Lund reviewed the ways the oil and gas industry manage MIC. In the study, Lund found that there was no universal standard for how to prevent MIC with cathodic protection (Lund et al., 2017). However, the study did reference the NACE SP0169 standard for “Control of External Corrosion on Underground or Submerged Metallic Piping Systems,” recommending an electropotential of -0.950 mV in the presence of sulfate reducing bacteria (Lund et al., 2017).

4.1.3 Material Effects

The final variable for the corrosion-fatigue crack growth rate of a steel is the steel itself. The Adedipe review of corrosion-fatigue specifically focused on the offshore wind sector breaks steels up into three main categories (Adedipe et al., 2016):

1. Conventional steel: Yield strength around 350 MPa

2. High-strength steel (HSS): Yield strength between 400 and 600 MPa
3. Very high-strength steel (VHSS): Yield strength between 700 and 900 MPa

According to their review, while there has been interest in using HSSs for offshore structures, there are two major challenges that have prevented their use. First, HSSs are not easily weldable compared with mild steels. This is a major concern, as any defect in the weld would lead to stress concentrations that can dramatically reduce the fatigue life of the detail. Second, HSSs are more susceptible to hydrogen embrittlement than conventional steels. It has been demonstrated in previous sections on cathodic protection and water chemistry that hydrogen production is a major concern in a marine environment. According to the review article, it is believed that newer types of conventional steel will outperform HSSs in corrosion-fatigue because hydrogen embrittlement plays a significant role in crack growth.

The conclusions drawn the Adedipe review are supported by another review paper from van Es that focuses on the application of HSSs and VHSSs in offshore structures generally (van Es, Slot, Steenbergen, Mailjaars, & Pijpers, 2018). The van Es review found that in some studies an increase in yield strength led to an increase in fatigue. However, other studies on welded specimens found that this increase was reduced compared to the base metal. It also states that these studies were for pure fatigue. When comparing studies of corrosion-fatigue crack growth using the Paris Equation, there was no noticeable improvement for HSSs or VHSSs. There does not currently seem to be much support in the literature for the use of HSSs in offshore wind support structures in the near term. New developments in construction and the prevention of hydrogen embrittlement would be required to use HSS in offshore wind foundations.

The last consideration for steel type is the type of steel treatment. After the SLIC testing, another project from the same research group studied the corrosion-fatigue crack growth rate of different

subgrades of S355 steel. The SLIC project in 2017 tested S355G8+M, while the newer tests were done on S355G10+M (Igwemezie, Mehmanparast, & Kolios, 2018). These tests were compared with testing from Scott/Thorpe in the 1980s that used S355J2+N. The M from the subgrade is shown for thermo-mechanical control process (TMCP) steel. Thermo-mechanical control processing is a modern way to process steel that is designed to increase homogeneity of the final product. The N from the subgrade stands for regular normalized steel. TMCP steel is more expensive than normalized steel. After running the additional corrosion-fatigue tests on the more expensive steel subgrades, the study found that the TMCP steel did not have a greater corrosion-fatigue resistance than the normalized steel, as seen in Figure 37 (Igwemezie et al., 2018).

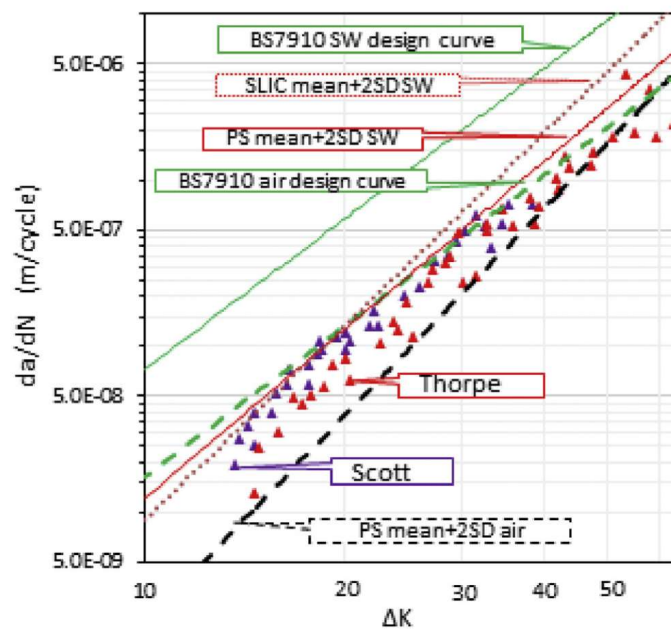


Figure 37. Paris plot comparison of steel grades TMCP (SLIC & Present Study) vs normalized steel (Scott & Thorpe) (from 2018 Igwemezie paper)

4.2 Summary of Past SN Curve Testing

While the LEFM testing is good for identifying trends and identifying critical variables, it is not used as often as SN curve analysis for design and research. Most research utilizing field data from offshore wind installations relies on Damage Equivalent Loads which are derived from SN curves. More information on the use of SN curves for continuing useful life calculations is discussed in Chapter 5. The first half of this section provides an overview of relevant metadata from fatigue tests collected as a part of database work done for MACEC. The second half of this section investigates corrosion-fatigue testing based on the literature including several review articles.

4.2.1 Summary of Metadata from Database

With funding support from the MassCEC, a database of corrosion fatigue test results from multiple different programs was created at Tufts. The test database contained over 1,000 data points from 122 SN curves generated from a variety of testing programs ranging from the 1980s to 2016. Table 5 shows the different years, main authors, sources, and names of the different test programs. The names of the test programs are an in-house style. In some cases, the name given is the name the test data was given in a larger report in other cases the name given to the test data is the lab where the testing was done. The test data currently in the database spans multiple decades from the early 1980s to 2019.

Table 5: List of the Testing Programs in the Database

Testing Program	Authors	Year	Source
UKOSRP	N/A	1980s	1994 TWI Report King
Canadian	Mohaupt	1987	1994 TWI Report King
Dutch/ECSC	Van Leeuwen	1981	1994 TWI Report King
Japanese	Iwasaki	1986	1994 TWI Report King
Norwegian	Solli	1981	1994 TWI Report King
SLIC	Consortium	2019	SLIC Consortium Report
FATHOMS	ECRFCS	2010	FATHOMS ECRFCS Report
Hannover	Schaumann	2013	Schaumann Paper 2013
DegradO	Collmann	2017	Collmann Paper 2017
Hannover	Schaumann & Collman	2018	S & C Paper 2018
KIT	Gkatzogiannis	2019	Gkat Paper 2019
Ibaraki University	Kobayashi	1999	Kobayashi Paper 1999
Chinese Academy of Sciences	Li	2006	Li Paper 2006
DTU Thesis	Ólafsson	2016	Ólafsson Thesis DTU 2016

The data is divided into a series of S-N curves. Each curve is defined as any number of specimens that are tested with a unique set of conditions. In some cases, there are not enough points to really make a meaningful S-N curve, but the points are still gathered so they can be compared with points from other test programs.

Table 6 shows the definitions of the different categories of metadata. This metadata is also collected in the Master Database Tracker.

Table 6: Table of metadata associated with each curve

Category	Definition
File Name	Name of the file in the S-N Folder. Name is simple to allow for easy import to MATLAB. Each cuve is its own excel file.
Testing Program	Name of testing program the curve comes from.
Authors	Authors from study. Not always easily available. Sometimes testing program name is used instead for identification.
Year	Year of the study. Also not always obvious sometimes the decade is given.
Environmental Condition	In-air testing vs free corrosion testing vs cathodic protection testing
CA or VA	Constant Amplitude or Variable Amplitude Testing
Load Method	4 pt bending (4 pt) vs Cantilever bending vs Axial loading
Thickness	Thickness of specimen
Weld Type	Type of weld (ie k-butt vs butt weld vs cruciform weld) (SIMPLIFY TO DNVGL categories later)
Weld Treatment	How is the weld treated (i.e. grinding, shot peening, as welded)
Frequency (Hz)	Frequency of Load Being Applied. NOTE: For in air a range is sometimes given in paper/reports. The high end of this range is listed.
R	Load ratio used in test
Temp (C)	Temperature of Seawater used in Testing (If unknown assume approximately 10 Deg C)
Electropotential (mV)	Electropotential of the metal if Cathodic Protection Used in Seawater
# of Specimens	Number of specimens used to generate the curve
Source	Source of datapoints. SOME DATA POINTS COME FROM REPORTS NOT PRIMARY SOURCES
Notes	Notes from John

The Master Database Tracker file also shows that each curve is given its own excel file. This was done to make it easy to import the files from excel into MATLAB as structures. This means that there are two ways to select relevant data. One method is to manually tell MATLAB what files to import based on the Master Database Tracker file. For example, if the user wanted to analyze only UKOSRP curves they could import the files named S-N Curves 1-23. The other method is to import all the S-N curves and then filter the relevant curves using the metadata. The user could filter out all the in-air curve testing and then only compare the cathodic protection and free corrosion data. The MATLAB file for importing the curves can be provided at request.

Comments on Test Quality & Quantity

The following tables and figures show a breakdown of metadata in the test database. Table 7 breaks the tests up into categories by the testing environment: in-air, cathodic protection, and free

corrosion conditions. It is relevant to note that for cathodic protection there can also be several subcategories based on the electropotential of the metal (i.e. -0.800 V, -0.700 V, -0.900 V, etc.). Table 8 shows the variety of different loading methods used across different tests. The stress distribution across the cross-sectional area of the specimen depends on the loading method.

Table 7: Comparison of Environmental Conditions

Environment	# of Curves	# of Points
In-air	27	223
Cathodic Protection	25	204
Free Corrosion	22	118

Table 8: Comparison of Loading Methods

Loading Method	# of Curves
Axial	38
Cantilever	29
4-Point Bend	47
3-Point Bend (T-Joint)	8

In addition to the tables, two histograms are provided. Figure 38 shows that for many of these “curves” there are fewer than 10 specimens tested. This makes sense logically, because for the in-situ corrosion tests, the frequency cannot be increased to make testing faster. As a result, the “curves” for some of these projects do not have enough points to really make a meaningful statistical analysis. Instead, the understanding of the impact of corrosion on the fatigue life of a weld needs to be made based on the results in aggregate and a comparison between these different test programs. Figure 39, on the other hand, shows the specimen thickness tested. Compared with monopile walls that can get up to 100 mm thick, the specimens in the database are not very representative. The initial work for the database focused on collecting corrosion-fatigue testing.

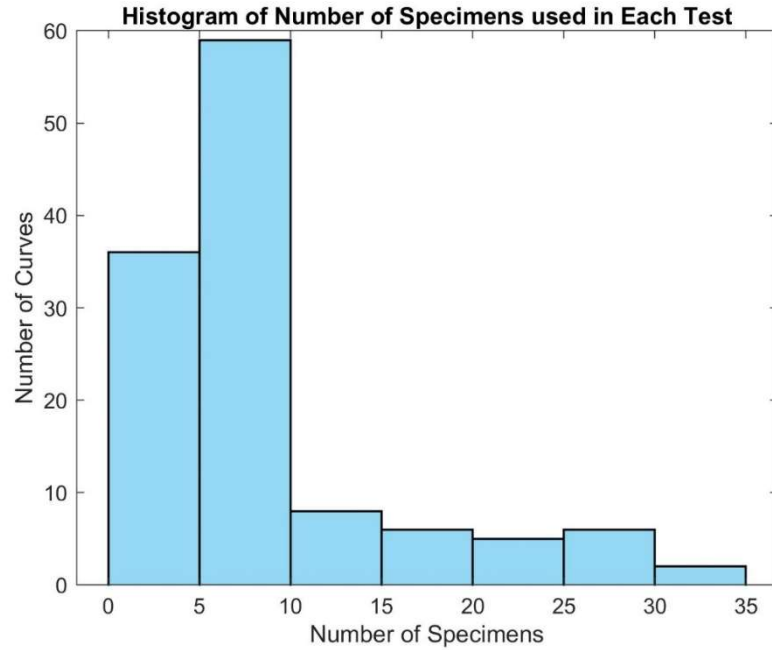


Figure 38: Histogram of Number of Specimens per Curve

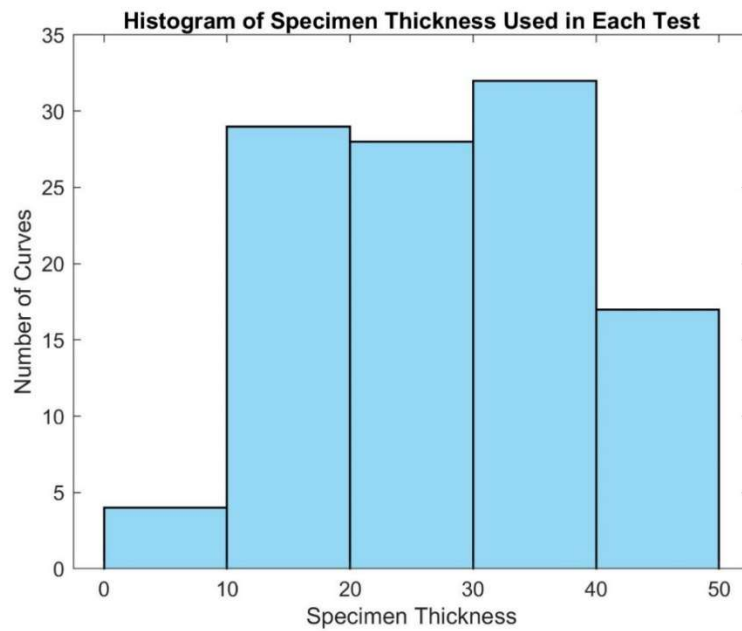


Figure 39: Histogram of Specimen Thicknesses Tested

A major source for the data base is a report archived by the HSE in 1994 contained additional details about testing programs cited in the 1999 background document (TWI, 1994). This report included

data from 6 studies across 5 countries, see Table 9. The testing programs are referenced by their country of origin: the UK, Canada, Holland, Japan, and two from Norway.

Table 9. Comparison of testing programs (information from 1994 TWI report)

Country	Year	Joint Type	Temp (C)	R- Ratio	Failure Criteria	Frequency for Seawater (Hz)	Thick-ness (mm)
Britain	1984 (Phase II) 1975 (Phase I)	K butt and longitudinal NLC fillet	5 to 8	0 and -1	Crack extends about halfway through thickness	0.17	38
Canada	1987	T joint with top of T in 3-point bending	5	0.05	Crack depth is 1/2 plate thickness	0.2	26 & 76
Holland	1981	Transverse non-load-carrying fillet with full penetration	20	0.1 and -1	Crack depth is 1/2 to 1/3 plate thickness	0.2	40 & 70
Japan	1986	Transverse non-load-carrying fillet weld	10	0	Decrease of load to 80% value	0.17	20
Norway	1987	Transverse non-load-carrying fillet weld	10	0.1	Excessive deflection	0.1 to 1.0	30 & 25

Table 9 reveals that there was a lot of variation in testing parameters and weld properties across testing programs. For example, each program used slightly different definitions of failure. The Holland tests were run at a significantly higher temperature than the rest. The Norwegian tests were run at two

different frequencies. Most importantly the programs tested a variety of weld classes and used different loading techniques. The impact of corrosion conditions for the British testing had to be corrected in a 1999 report because the corrosion and in-air tests were run with different loading devices, see Table 10. The testing from this era covered a variety of conditions and weld classes which leads to a large spread in the results that is discussed in the next section.

Another concern with this set of test data is that it is not very representative of modern offshore wind monopiles. First this testing was conducted in the 1980s which means the quality of steel is not representative of modern steels. Second, most of the welds tested in the programs were not D or C1 class welds, i.e. buttwelds. The 1999 background report discusses the ERFs in terms of T-butt and cruciform joints and the ERFs found in these studies have been applied to all weld classes in the S-N curve analysis (HSE, 1999). Finally, the thickness of most specimens is not representative of the thickness seen in offshore wind monopiles which can get more than 100 mm thick plate on a monopile butt weld.

4.2.2 Key Variables from SN Testing

There is less corrosion-fatigue SN testing than LEFM testing. This is in part because in-air fatigue testing is often sped up by increasing the frequency of loading to about 5 Hz. As seen in the previous section with LEFM testing, corrosion is a time dependent process, so the corrosion-fatigue effect is frequency dependent. This makes it very time consuming to run these tests. However, the limited amount of data makes it difficult to make definitive statements about the SN curves. This section breaks up the effects into five primary effects: the environmental reduction factor, the effect of the weldment itself, the thickness effects, and variable amplitude loading.

Environmental Reduction Factor

The impact of free corrosion and cathodically protected steel conditions is represented by the environmental reduction factor ERF defined in Equation 7. Health and safety executive (HSE) guidance

documents from 1990 and 1995 are cited as the justification for the ERFs in DNC-RP-c203 (Lotsberg, 2019). These specific documents were unable to be found but a copy of a HSE report from 1999 summarizes the results from testing described in the 1990 and 1995 reports (HSE, 1999). The 1999 document provides a table comparing the ERFs from multiple testing programs, see Table 10. Table 10 shows there is significant variability; the range of ERF for free corrosion over 10^6 cycles was 1.7 to 2.7. However, it is possible to see how an ERF of 3 for free corrosion and 2.5 for cathodic protection when the number of cycles is below 10^6 was ultimately selected.

$$ERF = \frac{\text{In-Air \# of Cycles Until Failure}}{\text{Free Corrosion \# of Cycles Until Failure}} \quad \text{Equation 7}$$

Table 10. ERF table from 1999 HSE report

Environment	Source	Range of fatigue lives (N3)	Average ERF
Free Corrosion	UKOSRP	< 10^6	1.4*
Free Corrosion	ONP	< 10^6	3.2
Free Corrosion	ALL DATA	< 10^6	2.6
Free Corrosion	UKOSRP	> 10^6	1.3*
Free Corrosion	ONP	> 10^6	2.7
Free Corrosion	ALL DATA	> 10^6	1.7
C.P. -0.8 to -0.9 V	UKOSRP	< 10^6	1.3* 2.23**
C.P. -0.8 to -0.9 V	ONP	< 10^6	2.74
C.P. -0.8 to -0.9 V	ALL DATA	< 10^6	2.46
C.P. -0.8 to -0.9 V	UKOSRP	> 10^6	0.5* 1.2**
C.P. -0.8 to -0.9 V	ONP	> 10^6	2.54
C.P. -0.8 to -0.9 V	ALL DATA	> 10^6	1.20
C.P. -1.0 to -1.1 V	UKOSRP	< 10^6	2.2*
C.P. -1.0 to -1.1 V	ONP	< 10^6	2.7
C.P. -1.0 to -1.1 V	ALL DATA	< 10^6	2.5
C.P. -1.0 to -1.1 V	UKOSRP	> 10^6	1.1*
C.P. -1.0 to -1.1 V	ONP	> 10^6	1.4
C.P. -1.0 to -1.1 V	ALL DATA	> 10^6	1.2

Notes: C.P. Cathodic Protection
 ONP Other National Programmes (see text)
 * Uncorrected UKOSRP data
 ** Corrected UKOSRP data

Figure 40 is originally from a 1994 report and has been redrawn; it summarizes the same tests presented in Table 6. This figure shows that there was a significant scatter in the ERF across different

testing programs. In some cases, such as the Britain (aka UKOSRP) data with $CP = -0.850V$ there is no clear ERF. In addition to the significant scatter in the results the report makes other observations that show the uncertainty of these measurements. First, in all the SN curves for cathodic protection and free corrosion conditions there were very few data points above $1E6$ cycles. Second, some of the SN curves have unusual slopes. In the redrawn figure, the square icons represent tests that had unusual slopes, and the ERF had to be calculated by enforcing a slope of $m = 3$. Finally, for the Dutch tests there was a temperature correction factor because they were tested at 20 C . This correction was calculated using crack growth data and could have introduced some uncertainty. While the ERFs used in the modern era are based on this early SN curve data it is important to note that the data is quite varied.

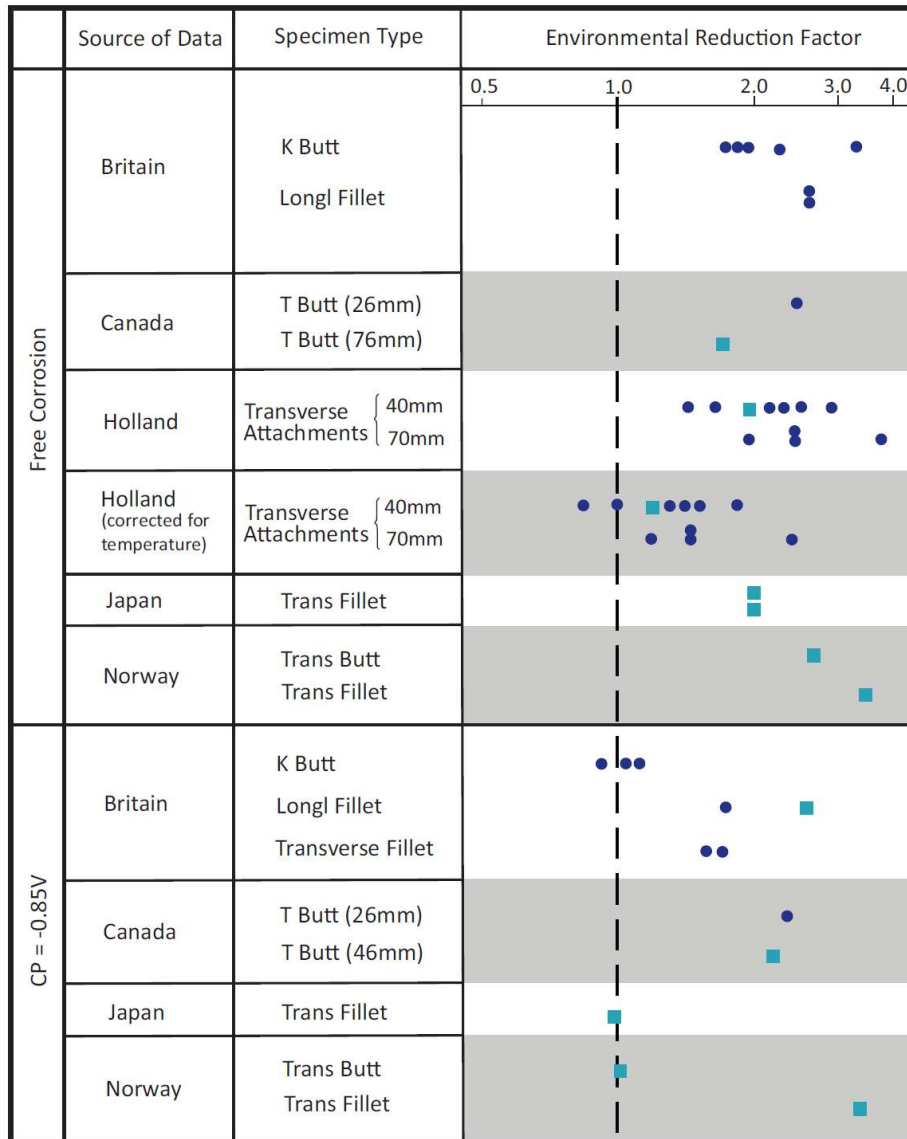


Figure 40. ERF comparison (redrawn from 1994 TWI report)

Additionally, the ERFs for free corrosion curves do not stay consistent in the high-cycle regime. This is because the free corrosion curve does not have a change in slope like the in-air and cathodic protection curves. Figure 41 shows this relationship graphically while Table 11 provides values for context. Above $1E7$ cycles there is no difference between the cathodic protection curve and in-air curve. However, by the time the curve reaches around 20 MPa, the ERF for the free corrosion curve is over 20

rather than the original 3 for the high stresses. Intuitively, it makes sense that the free corrosion curve does not have an endurance limit, but it has huge consequences for any use of the free corrosion curve.

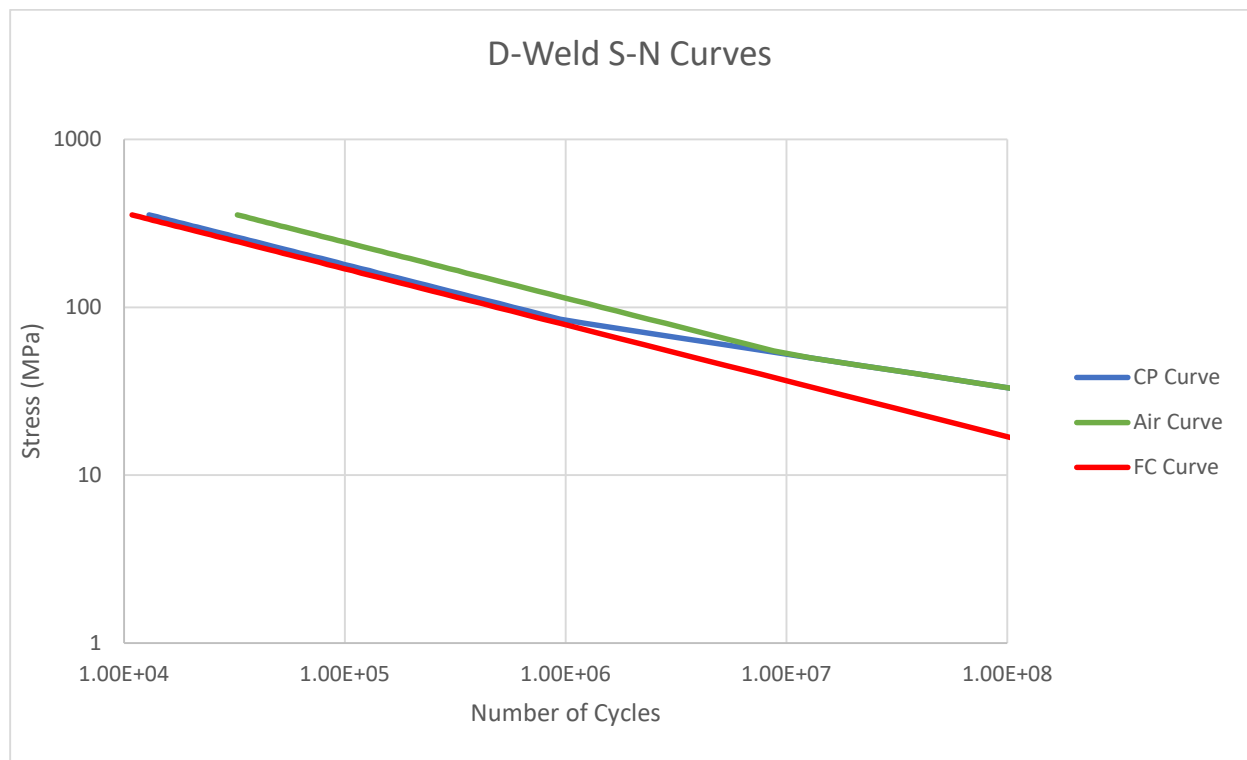


Figure 41. Comparison of DNV GL S-N curves

Table 11. Comparison of DNV GL S-N curves (Number of Cycles to Failure)

Stress (Mpa)	Air Curve	CP Curve	FC Curve	ERF (CP)	ERF (FC)
55	8.77E+06	8.02E+06	2.92E+06	1.09	3.00
50	1.29E+07	1.29E+07	3.89E+06	1.00	3.32
45	2.19E+07	2.19E+07	5.34E+06	1.00	4.10
40	3.94E+07	3.94E+07	7.60E+06	1.00	5.19
35	7.69E+07	7.69E+07	1.13E+07	1.00	6.77
30	1.66E+08	1.66E+08	1.80E+07	1.00	9.22
25	4.13E+08	4.13E+08	3.11E+07	1.00	13.28
20	1.26E+09	1.26E+09	6.08E+07	1.00	20.75
15	5.32E+09	5.32E+09	1.44E+08	1.00	36.88
10	4.04E+10	4.04E+10	4.86E+08	1.00	82.99

Weldments

Welding a metal changes two variables that affect its corrosion-fatigue life. First, the type of weld and manufacturing process affects the type of notch that is created, which acts as a stress concentration factor. This effect is discussed in depth in DNVGL-RP-C203 (2016). Second, as discussed earlier for residual stresses, the welding process heats the surrounding metal. In addition to causing residual stress, this heat changes the microstructure of the metal in what is defined as the heat affected zone or HAZ. In the review paper by Adedipe, several studies are discussed that investigated the fatigue resistance of the HAZ and found that it has a reduced fatigue resistance (Adedipe et al., 2016).

This relationship between the HAZ and reduced fatigue resistance was tested for corrosion-fatigue during the SLIC project. The SLIC tests had samples from the base material and samples taken from the HAZ (Adedipe et al., 2017). Figure 43 shows the part of the weld that is considered the HAZ. The results of these tests are seen in the mean Paris curves plotted in Figure 42. The base material (BM) and HAZ have similar Paris curves for the air and for the seawater conditions, respectively. This indicates that unlike the studies mentioned in the Adedipe review, there is no reduction in the fatigue resistance of the HAZ for corrosion-fatigue under free corrosion conditions (Adedipe et al., 2016). This would seem to indicate that the HAZ is a critical area for fatigue design because of the effects of pitting corrosion in the region. Future work should be done investigating corrosion pit behavior on welded steel.

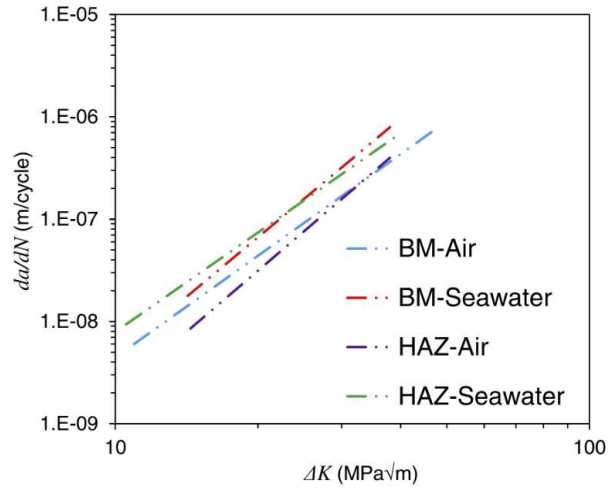


Figure 42. Paris plot comparison of heat affected zone (HAZ) and base material (BM) (from Mehmanparast 2017)

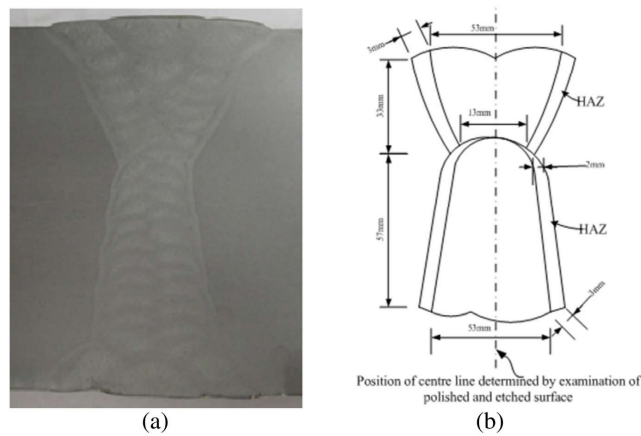


Figure 43. Diagram and photo of a girth weld. Shows the HAZ region. (from Mehmanparast 2017)

DNVGL-RP-C203 has equations to calculate stress concentration factors (SCFs) for different weld details. These equations are discussed in Chapter 5. In order to study stress concentration factors Kolios et al. used 3-dimensional laser scanning technology to create a detailed 3-dimensional finite element model of a butt weld similar to a D-class weld that would be found on a monopile (Kolios, Wang, Mehmanparast, & Brennan, 2019). The detailed finite element model was used to determine the stress concentration factor (SCF) for the notch created by the weld. An example of this can be seen in Figure 44

for a double butt weld made of two 50-millimeter-thick plates. There is a significant amount of variation in the SCF, especially for the front and bottom portion of the weld.

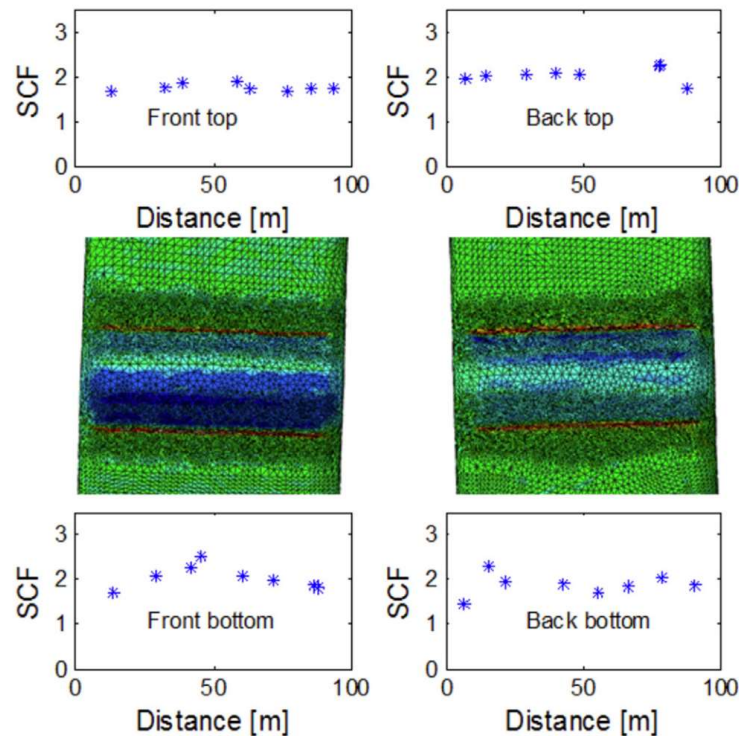


Figure 44. Distributions of stress concentration factors from detailed 3D laser scans (from Kolios 2019)

Corrosion can have a significant effect on the SCF of a weld. While a comprehensive study of this effect has not been identified, the issue did come up in a recent study (Gkatzogiannis, Weinert, Engelhardt, Knoedel, & Ummenhofer, 2019). In this study, the team tested the fatigue life of butt weld specimens that were subjected to real marine corrosion in the North Sea for two years. Surprisingly, the fatigue strength of the corroded specimens was longer than the fatigue life of the uncorroded specimens. They speculated that this may have had two causes. The first theory was that the corrosion smoothed out the notch from the weld. The second theory was that corrosion may have reduced residual stress in the weld. Even though this is not a comprehensive study, this case underlines how complexities of corrosion-fatigue interactions.

Thickness Effects

Another major component to determining the fatigue capacity of a weld is the thickness of the plates. Equation 8 comes from DNV GL c203 (eq 2.4.3). The equation shows where the thickness coefficient, k , is applied in the equation for corrosion-fatigue capacity.

$$\log(N) = \log(\bar{a}) - m \log \left(\Delta \sigma \left(\frac{t}{t_{ref}} \right)^k \right) \quad \text{Equation 8}$$

There have been reviews of test data about the thickness coefficient. In a 2018 review of test data on thick welded specimens in air, Pedersen found that the thickness coefficient may capture several competing effects on weld fatigue life (Pedersen, 2019). These effects include residual stresses, weld lengths, and misalignments. In addition to hypothesizing that the thickness coefficient captures a variety of effects, the review paper concludes that existing thickness coefficients may be overly conservative. This can be seen in Figure 45 from the Pedersen paper.

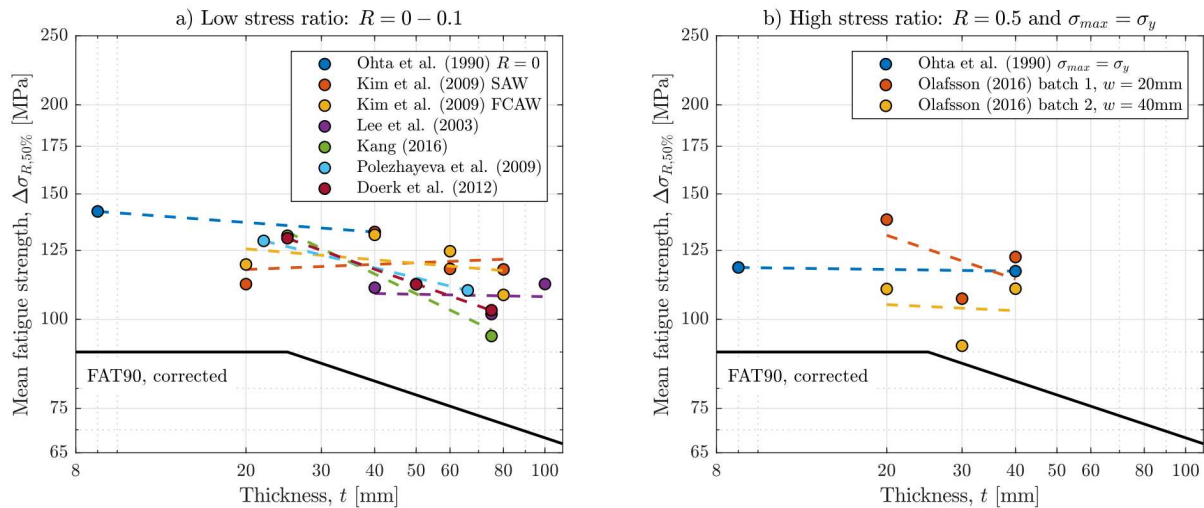


Figure 45. Comparison of thickness correction test data with codes (from Pedersen 2018)

Figure 45 compares different test data sourced in the review paper against the FAT 90 weld class in the International Institute of Welding (IIW) recommendations. For comparison, the DNVGL-RP-C203 thickness coefficients used in the IIW recommendations are the same, and the FAT 90 weld class is equivalent to the DNVGL-RP-C203 D class S-N curve. It is also important to remember that this review was looking at in-air testing. It is not clear that the thickness effect for in-air testing would be the same as the thickness effect for in-situ corrosion-fatigue testing.

Pedersen also found that fatigue strength may be correlated with specimen width in addition to its thickness. Because the specimens reviewed have several different widths, it is difficult to make a conclusive decision based on the width alone. Related to this idea is the fact that other research has shown that manufacturing techniques have a significant impact on the fatigue life of a weld. This is addressed in the Pedersen paper as a technological size effect. Other studies examine this effect using 3-D scanning to measure local weld geometry (Kolios et al., 2019). In their study, Kolios et al. found that there was a significant impact from the number of weld passes and the weld geometry. Another study from Zhao and Hsu examines the thickness effect in combination with seawater testing. In their study they also found that the thickness effect in the codes was conservative for in-air testing. However, there was not enough test data to make a claim about the effect with cathodic protection or free corrosion conditions (Zhao & Hsu, 2020).

Variable Amplitude Loading

One key assumption in S-N curve analysis is that damage accumulates linearly. This assumption is known as the Palmgren-Miner rule and states that the load sequencing does not matter. However, it is well documented that load sequencing does matter for variable amplitude loading fatigue analysis. This assumption is built into DNVGL-RP-C203 (2016) for fatigue life calculations using S-N curves.

DNVGL-RP-C203 discusses the uncertainty associated with the Palmgren-Miner rule in Section 9, “Uncertainties in Fatigue Life Prediction” (DNV GL, 2016b). According to the recommended practice, “the uncertainty in loading is included in addition to uncertainties in S-N data and the Palmgren-Miner damage accumulation rule” (DNV GL, 2016b). The uncertainty of the Palmgren-Miner rule is represented by a logarithmic distribution with a median of 1.0 and a covariance of 0.3. The source of this uncertainty distribution is a 1985 paper in which the author examined data from multiple fatigue tests and determined the distribution mostly from “professional judgement” (Wirsching & Asce, 1985).

Another major consideration for variable amplitude loading can be seen in the SN curves themselves. Most testing for SN curves goes up to $1E7$ cycles at most. This is because around this point there is a fatigue limit for in air testing. In other codes the fatigue limit is seen as a horizontal point on the SN curve and no damage occurs below it. However, in the Eurocode and DNV SN curves the Haibach adjustment is made at the fatigue limit (Lotsberg, 2021). Instead of a flat point causing no damage the inverse slope of the curve changes from $m = 3$ to $m = 5$ and the curve continues. The consequences of this adjustment are described in Chapter 5 (Haibach, 1979).

This means that the SN curve can be seen as having two halves. The first half below $1E7$ cycles is built based on constant amplitude test data. The second half exists due to variable amplitude loading and comes from the Haibach adjustment. The consequences of this can be seen in a 2021 review article from Zhao that sought to use a database with many of the same datapoints I presented earlier to recalibrate the design fatigue factors (DFFs) via a FORM analysis (Zhao, 2021). However, the value of the calibration is limited because the test data only goes up to $1E7$ cycles (i.e. the first half of the SN curve). Zhao’s analysis is transparent about this limitation, but this does mean that depending on where the damage is coming from, calibrating the DFFs using information from the first half of the curve is not appropriate. This will be discussed in more detail under the variable amplitude loading.

Quantity of Data

There is also another limitation to Zhao's database work (Zhao, 2021). There were not enough datapoints with the D-curve or T-curve for cathodic protection or free corrosion conditions. This is unfortunate since the D-curve would be the most interesting for the submerged zone of a monopile and the T-curve is typically used for offshore jacket structures. Analysis for in-air conditions is interesting and helpful for the splash zone some of the most interesting SN curves do not have enough data for analysis.

4.3 Conclusion and Key Findings

Most of the recent testing done on corrosion-fatigue testing has been done with LEFM specimens to study the Paris Law constants. While this is a useful endeavor, the tool of choice for most design and remaining useful life decisions remains the SN curve. Most of the data used to justify the original SN curves for seawater conditions still comes from the 1980s. Recent efforts to re-examine the SN curves have been unsuccessful due to a scarcity of data points. In addition to a general lack of data, the SN curve can be thought of having two parts the first half derived from constant amplitude testing and the second half coming from variable amplitude loading. Because there is not much variable amplitude testing this second half of the SN curve has an inherently higher uncertainty even if typical models for SN damage do not account for this. The next chapter uses data from a real operational wind farm in order to bridge the gap between fatigue damage and fatigue capacity.

Key Findings:

- Recent corrosion-fatigue testing (SLIC) focused on compact tension specimen testing to determine the Paris Law coefficients for linear elastic fracture mechanics (LEFM). This testing updates relationships that were originally established in testing programs from the 1980s that identified key variables such as:

- Testing Frequency – Corrosion is a time dependent process thus corrosion-fatigue crack growth rate is very sensitive to frequency.
- Temperature – Temperature is an interesting variable because it was not a focus of modern testing and one of the most popular testing programs Scott & Thorpe found that the crack growth rate doubled when temperature changed from 5 C to 20 C. This could have had a major impact on the design of offshore wind farms in warmer waters such as off the coast of Virginia. However, a review article from Jakubowski found the Scott & Thorpe result to be an outlier.
- Cathodic Protection – The best variable to measure the effectiveness of cathodic protection is the electropotential of the metal. When the metal is under normal cathodic protection conditions –850 mV the fatigue crack growth rate is around 2.5 times faster than in-air crack growth rates. Under free corrosion conditions the rate is even faster, 3 times higher than the in-air crack growth rates. It is important to note that when steel is over protected above -1000 mV the crack growth rates get higher.
- Material Type – Most foundation components are made using typical low carbon steel such as S355. Testing has shown that high strength steels can be more susceptible to hydrogen embrittlement which makes them more difficult to use in a marine environment. Modern testing also shows that S355 steel that undergoes more advanced processing (TCMP) does not have a better corrosion-fatigue performance than regular normalized steel.
- SN testing is more expensive and difficult to run because it covers the entire fatigue life of the detail including crack initiation. When testing in-air it is possible to accelerate the tests by increasing the frequency to around 5 Hz but for corrosion-fatigue testing that is not possible. The limited amount of SN testing shows:

- Looking to the past, the environmental reduction factors that represent the fatigue life reduction due to corrosion conditions are very scattered. The use of 3 for free corrosion and 2.5 for cathodic protection is reasonable based on the available data but the results are not well clustered.
- The thickness adjustment in the recommended practices is likely conservative based on the limited amount of testing available for thick specimens above 50 mm thick plate.
- Recent work using a database of corrosion-fatigue testing found that there was not sufficient testing available to build an uncertainty model.
- Even if there was enough testing available constant amplitude it would not be relevant for the second half of the SN curve with the shallower slope $m = 5$. This has consequences for Chapter 5.
- While LEFM testing only accounts for the long crack growth phase of fatigue damage they are often used to investigate the relative importance of different variables. For example, one review of SN testing from the 1980s corrected temperatures for one of the testing programs using LEFM behavior. The ERFs selected for the SN curves are also 3 for free corrosion and 2.5 for cathodic protection which is in part due to the SN data but also agrees with LEFM data.

Primary Contributions of PhD Research

Key limitations in corrosion-fatigue research are identified. A deep review of the early 1980s testing done to establish the environmental reduction factors of the original SN curves shows that there is significant variability in important metadata such as frequency and temperature. There is also variability in the ERF results themselves. These findings support work done by Dr. Wangwen Zhao who concluded that there was not enough cathodic protection and free corrosion data on butt welds to build an uncertainty model. The limitations about how constant amplitude SN curve testing only supports the

curve up to 1E7 cycles are further explored in the next chapter when fatigue demand from a monitored offshore wind turbine is introduced.

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Chapter 5 Fatigue Demands & Capacity

In 2023 the US Department of Energy (DOE) Offshore Wind (OW) energy strategy defined the (Near-term Offshore Wind) NOW initiative focused on reducing the cost of fixed offshore wind over the next 5-10 years (Anstedt & Sheri, 2023). One key activity within the NOW initiative is to “advance autonomous maintenance by developing tools and strategies that reduce costly on-site maintenance needs, increase safety, and prolong turbine life”. In addition to this initiative from the US DOE there is a wide range of projects in Europe focused on decreasing operations and maintenance costs (O&M) such as the ROMEO project (ROMEO).

Monitoring the offshore wind support structure (OWSS) (i.e., tower and foundation) is a prime candidate for reducing O&M costs. According to a systematic Failure Mode Effects and Criticality Analysis (FMECA) from Scheu et al. in 2019, about a third of the critical failures of offshore wind turbines were related to the support structure (Scheu et al., 2019). This includes a variety of failures such as excessive corrosion, fatigue damage, and failures in the connection between the tower and transition piece. Structural Health Monitoring (SHM) is an important tool for monitoring the OWSS via instruments that collect a range of data such as accelerations, strains, environmental conditions, and tilts (NGI, 2017). In a theoretical exercise, Martinez-Luengo et al showed that the use of SHM systems could supplement work typically done via visual inspection and reduce total O&M costs (Martinez-Luengo, 2019).

As an increasing number of offshore wind structures have been instrumented with SHM systems, there has been a greater focus on utilizing the collected data. Digital twin research for OWSS combines the data collected via SHM with finite element models of the structure to process the data (Svendsen, 2022). These digital twin models can have a variety of uses including fatigue damage estimation, informing inspection activities, and ultimately damage identification.

In addition to the general recommendations from entities such as the Norwegian Geotechnical Institute (NGI, 2017) and Ramboll (Svendsen et al., 2022), the application of SHM and digital twins to OWSS is an area of very active research. Augustyn et al created a probabilistic framework that updates the structural reliability information of the support structure in a way that could inform inspection and maintenance activities (Augustyn et al., 2021). This kind of reliability updating framework can also be seen in the DNV recommended practice for Probabilistic Method for Planning of Inspection for Fatigue Cracks in Offshore Structures (DNV, 2015).

In addition to work focused on informing inspections, these tools can be used to estimate the remaining useful life and measuring fatigue damage. Estimating the amount of fatigue damage on an offshore wind support structure is a major focus of research because offshore wind turbines are highly dynamic structures subject to millions of load cycles over their lifetime. The fatigue limit state (FLS) is often highlighted as a controlling factor for offshore wind support structure design and is a major focus of offshore wind foundation design (Xi et al, 2021; Velarde et al., 2020; Arany et al, 2017). In their work creating reference monopile designs across the US East Coast using the 15 MW reference wind turbine from the IEA, Mroczek et al stated that in 11 out of 12 cases the FLS controlled the monopile diameter and thickness (Mroczek et al, 2024). As offshore wind farms use bigger turbines and move into deeper waters, the relative importance of the FLS is expected to increase (Velarde et al., 2020). Work focused on estimating the fatigue damage of offshore wind support structures and the remaining useful life are important in the industry. For example, Mai et al used real oceanographic data to update the remaining useful life of monopile foundations (Mair et al., 2019), and Pacheco-Blazquez et al utilize a digital twin framework to calculate the remaining useful life of theoretical floating offshore wind turbines (Pacheco-Blazquez et al., 2024). Generally, research in this area is primarily focused on assessing fatigue demands and processing data to count relevant stress cycles and find damage equivalent loads.

While there is a wide spectrum of research focused on calculating fatigue damage on OWSS and using fatigue damage indicators as a metric, there is often less of a focus on how the capacity assumptions may affect the work at large. This work will explore the effects of capacity assumptions using data from Block Island Wind Farm (BIWF) and an example case study. The paper is broken into the following sections:

- 1.) Literature review on how fatigue damage estimates are calculated in the literature
- 2.) Overview of Methodology and Summary of BIWF details
- 3.) Analysis of capacity assumption effects on fatigue damage estimation using BIWF data

5.1 Background

Fatigue damage of the OWSS is a major area of research for the OW industry and academia. The process can be broken up into three closely interrelated subfields. First, the stresses at key points of the OWSS need to be estimated to find the fatigue demand via rainflow counting of stress cycles. This demand side work includes the design of sensor systems to collect data, the tools needed to process and interpret the data, and methods to transfer knowledge from one level of the structure to another. Second, physical testing of small-scale specimens in labs is done to validate and improve the fatigue damage models. This includes studies focused on the effects of plate thickness, weld details, weld treatments, corrosion conditions, and crack growth rates. Finally, these two domains are combined when the fatigue demands are plugged into damage models to calculate fatigue to be used as a metric. This last step is the glue that connects field observations to the small-scale specimen testing. However, there are not many examples that show how the assumptions being made on capacity modeling can affect the understanding of fatigue demands.

5.1.1 Fatigue Demand Work

The first step of fatigue damage estimation is to estimate the nominal stresses at a point of interest. The ease of this depends on the quantity and placement of sensors relative to the location of interest. A key theme across all SHM and digital twinning work is that these systems should be built for a purpose and different monitoring goals will lead to different system design (Martinex-Luengo et al., 2019). For example, Mehrjoo et al optimized sensor placement based on purpose of the system while minimizing the cost of installing sensors at different points in the structure (Mehrjoo et al, 2022). Generally, it is far more expensive to install sensors on the foundation below the waterline than it is to install strain gauges and accelerometers above the waterline such as in the tower.

Using information from the tower to learn about fatigue damage on the foundation is a major area of research because it is easier to instrument the tower. In 2018, Ziegler et al created a strain-based load extrapolation algorithm to take Damage Equivalent Loads (DELs) from one sensor and apply them to a different level (i.e., tower to monopile) (Ziegler et al., 2018). In addition to models extrapolating based on DELs, work has been done using modal expansion to create virtual sensors on the submerged foundation when only accelerations and strains are collected on the tower. In their 2021 work, Augustyn et al found that modal expansion can be applied to a 5 MW wind turbine on a jacket substructure under simulated conditions (Augustyn et al., 2021). Similar work was also done by Henkel et al. on a simulated offshore wind jacket and found that the modal expansion method could be unreliable due to the high contribution of local modes to fatigue damage that are not captured by the global modes in the tower (Henkel et al., 2020). While it is not directly relevant to the jacket structure analyzed in this paper, research is also occurring to apply modal expansion to monopile structures (Iliopoulos et al., 2017).

5.1.2 Fatigue Testing & Models

In their review article on fatigue damage assessment for OWSS, Haselibozechaloe et al use *Figure 46*, seen below to show the stages of damage for corrosion-fatigue (Haselibozechaloe et al.,

2022). Broadly speaking fatigue damage, even under in-air conditions, can be broken up into crack initiation and long crack growth. This distinction is important because the two most common fatigue damage models are SN curves and linear elastic fracture mechanics (LEFM). SN curves are based on specimens tested until failure while LEFM analysis is typically based on the Paris Equation that is only valid for long crack growth.

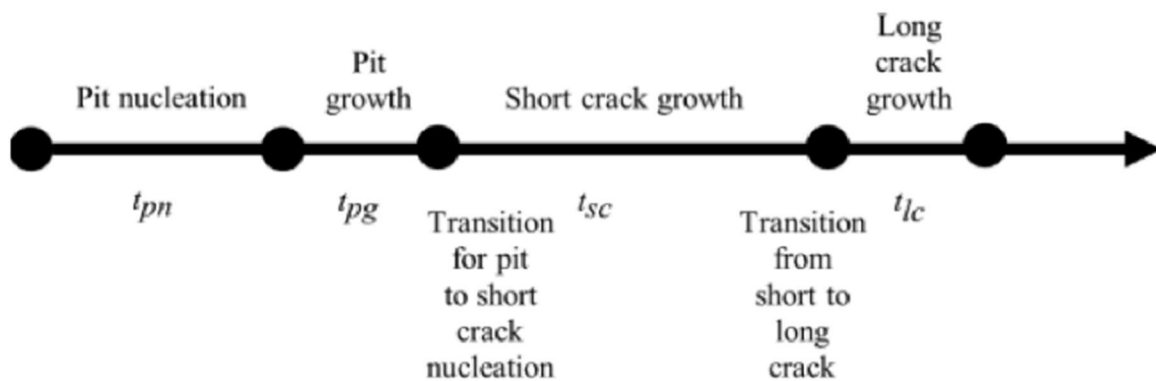


Figure 46 Steps of Fatigue Damage (Reproduced from Haselibozechaloe et al., 2022)

LEFM relates the stress magnitude and distribution near the crack tip to the size and shape of the crack, material properties, and nominal (not local) stress applied to the cracked component. Because it is based on stress magnitude at the crack tip, LEFM requires the initial size of a crack (or an estimation) as an input. The most common model for fatigue crack propagation is the Paris Equation (also known as the Paris law). The Paris Equation is an empirical relationship that relates the stress intensity factor range with the rate of crack growth per cycle. BSI-7910, “Standards Publication Guide to Methods for Assessing the Acceptability of Flaws in Metallic Structures” is a very common document referenced for Paris Law analysis (BSI, 2015). LEFM mechanics has been used in several research projects focused on a variety of variables such as variable amplitude loading effects (Maljaars et al., 2015), and crack growth under corrosive conditions (Mehmanparast et al., 2017; Igwemezie et al., 2018; Igwemezie et al., 2020). One major benefit of LEFM testing is that it typically takes less time than conventional SN fatigue testing. Test

duration can be a limiting factor for fatigue testing particularly for corrosion-fatigue testing where the effect is sensitive to frequency and tests cannot easily be accelerated (Adedipe et al. 2016).

However, when determining a remaining useful life in the context of SHM and digital twinning, many projects use SN curves since they do not require assumptions about the initial defect size and can be easier to implement. SN curves will be used for the analysis in this paper because SN curves are the most popular model when damage modeling for support structures. SN curves are created by testing specimens at constant amplitudes until they fail. Many of the tests that form the core of the current SN curves were done in the 1980s to support the offshore oil and gas industry (HSE, 1999; HSE, 2002; HSE, 2000). However, there have also been efforts recently to confirm the results of these previous tests from programs such as the SLIC project (Mehmanparast et al., 2024). Other efforts have focused on different steel marine structures such as risers (Horn et al., 2018). One key observation of this paper will be to examine the fatigue demand of the BIWF in the context of what SN curve data is available and where there are gaps.

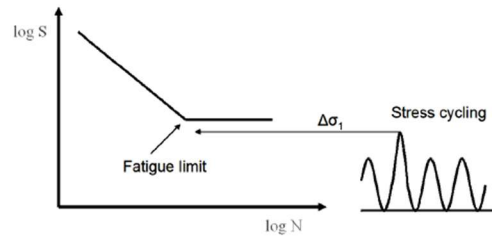
In addition to new SN testing, there has also been an effort to re-examine the SN curves based on databases of all testing done in the past sixty years. For example, Zhao in their database review of the DNV C203 SN curves found that in some cases the design fatigue factors (DFFs) suggested by DNV are conservative (Zhao, 2021). However, this work has two important caveats. First, the D and T curves with cathodic protection, which are some of the most important S-N curves analyzed by Zhao did not have enough data available to build an uncertainty model. This points to a general need for more testing under realistic maritime conditions, but this is made more difficult by the sensitivity of corrosion-fatigue damage to frequency. Second, most of the data used by Zhao comes from testing done before the knee point, $1E7$ for in air, which meant they were able to simplify the equations to use a single slope. However, in their review of the C203 recommended practice document, Lotsberg and Fjeldstad state that the largest contribution to fatigue damage for a C-curve applied to offshore wind foundations is around

1E7 cycles (Lotsberg & Fjeldstad, 2023). This would indicate that cycles above 1E7 cause a meaningful amount of damage and could cause issues for any reanalysis of the DFF based on test data prior to 1E7. Furthermore, in their same paper, Lotsberg and Fjeldstad state that while there is some debate about the slope of the S-N curve above 1E7 cycles the current slope of $m=5$ should be kept the same in the absence of new conclusive data.

These discussions around uncertainty in the S-N curves and test data availability highlight two key points. First for some conditions such as cathodic protection and free corrosion, there is significantly less data available compared to in-air testing. More testing or a new model for corrosion-fatigue damage is needed to make improvements to designs in the submerged zone. Second, much more is known about the fatigue behavior of specimens before the knee point 1E7 cycles than above it.

There is less certainty about fatigue behavior above the knee point in large part because that section of the curve is tied to variable amplitude effects. For example, Figure 47 taken from c203 shows how if all stress cycles counted in a series are below the fatigue limit, then a full fatigue analysis is not needed. However, if any of the stress cycles lie above the fatigue limit then a full fatigue analysis is needed, and the S-N curve is adapted following the Haibach rule such that at 1E7 the inverse slope changes from $m=3$ to $m=5$ (Haibach, 1979).

a) $DFF = 1.0$



b) DFF larger than 1.0.

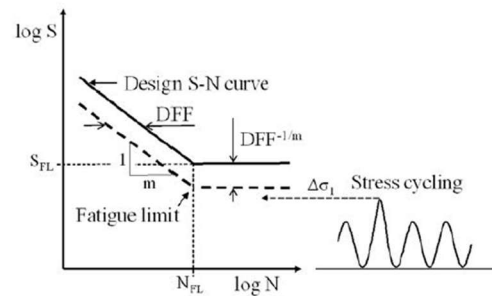


Figure 2-17 Stress cycling where further fatigue assessment can be omitted

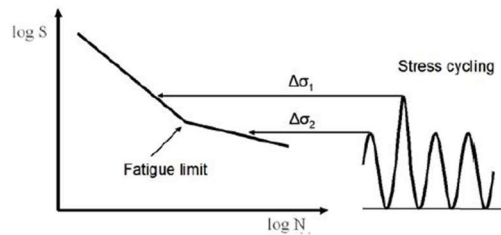


Figure 2-18 Stress cycling where a detailed fatigue assessment is required

Figure 47 Example of Variable Amplitude Effect (Taken from DNV C203)

5.1.3 Fatigue Damage Calculation

Presuming an S-N curve is going to be used, two more decisions are needed to calculate a damage estimate based on a given fatigue demand; the specific weld detail analyzed needs to be selected, and the stress time history needs to be adjusted to have an appropriate stress concentration factor if needed. The base metal fatigue performance is not expected to be relevant to the design (Nozari, 2020). Instead, the investigator needs to decide what weld details are the most interesting to analyze for the structure. For example, on OW monopiles the circumferential D class welds are common analysis points (Kuchma, 2020). Weld class selection will help inform SN curve selection. After a curve is

selected, the nominal stresses from the SHM/Digital Twin system need to be adjusted to more accurately represent the stresses found for that weld detail.

There are several different standards available with SN curves for fatigue analysis. Im and Chuong compared the parameters defining the S-N curves from five codes DNV, BS, ABS, IIW, and the Eurocode (Im et al., 2021). In their review, Im and Chuong found that the BS codes were the most conservative and looking at their comparison for the D-curve (reproduced in *Figure 48*); the biggest differences between the codes can be seen above $1E7$ cycles. In the research literature for OW, the DNV-RP-C203 document is by far the most popular. While there are subtle differences across standards, this is often not reflected in literature because of the ubiquity of the DNV C203 curves.

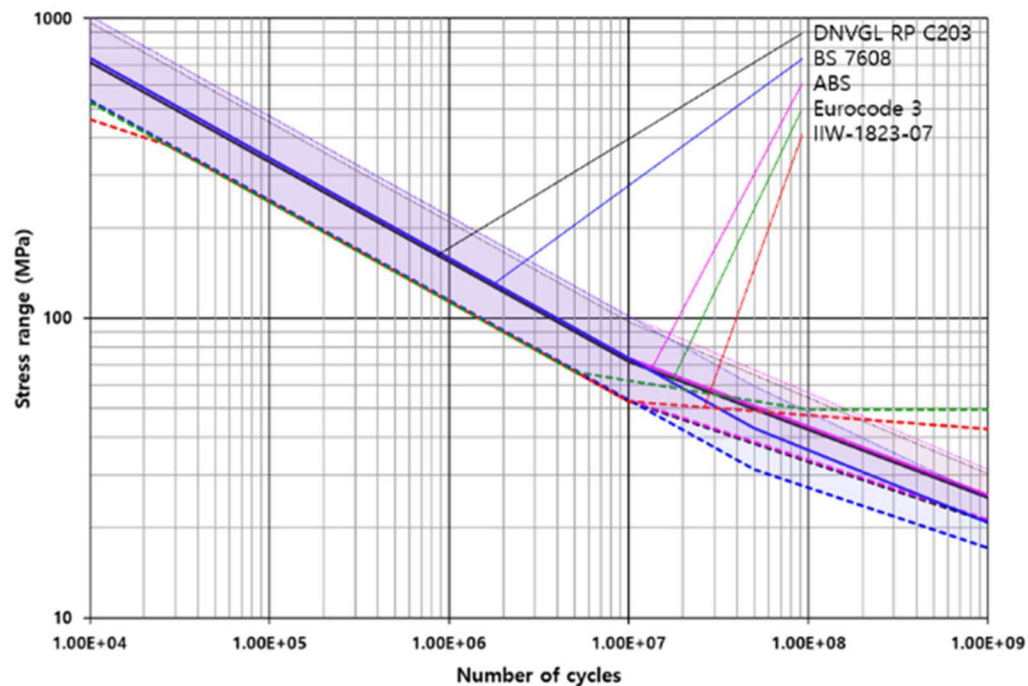


Figure 48 Comparison of SN curves (from (Im et al., 2021))

After the stress time series is calculated with the selected SCF the fatigue damage can be calculated using one of two general categories of metric: damage indices or damage equivalent loads (DELs). Damage indices are a unitless representation of cumulative fatigue damage from the histogram of stress cycles, see chapter 4. DELs portray the damage from a histogram of variable amplitude load

cycles as a single amplitude load cycle that would cause an equivalent amount of damage for a set number of cycles, i.e. 10⁷ (Natarajan, 2022). The equation used to calculate the damage equivalent stresses (DES) by Sadeghi et al. in their work on low frequency load cycles is presented in Equation 9 (Sadeghi et al., 2023).

$$DES = \left(\frac{\sum_{j=1}^{N_{blocks}} n_j (\Delta\sigma_j)^m}{N_{eq}} \right)^{1/m} \quad \text{Equation 9}$$

For many research projects the focus of the work is not to estimate the remaining useful life of the support structure, thus the capacity assumptions are not a focus. Instead of presenting the work with a damage index or remaining life estimate, DELs are used because they are a stable metric that is convenient to plot. They are very effective for comparing different distributions of load cycles (Sadeghi et al., 2023). For example, they have been used as a metric that can be extrapolated based on data collected from one year (Natarajan, 2022). DELs have also been used as a metric for training neural network models to estimate DELs based on turbine operational parameters (Perez-Campuzano, 2018). Other work has used DELs for training hybrid models using a mix of simulations and real data (Haghi et al., 2024). In addition to being used in more complex research focused on training models and extrapolating based on limited data and information, DELs are a common metric for just reporting damage across different variables like wind speed (Iliopoulos, 2017). DELs were also applied to research on the relative importance of low frequency cycles on fatigue (Sadeghi et al., 2023; Sadeghi et al., 2022). While DELs are a very powerful tool and are appropriate for these cases when the point is comparison, they do not have a direct relationship with actual damage because as seen in Equation 9 they are only dependent on the slope and do not capture the real nature of the bi-linear SN curve, see Figure 48.

Generally, much of this research on offshore wind support structures does not emphasize the capacity assumptions in the fatigue analysis. When DELs are the primary metric the only variable that is relevant is the inverse slope, m . Since m can be either 3, 4, or 5 according to the detail and location on

the SN curve DELs can be presented with all three. Since DELs are not meant to account for specific structural details, they do not provide much detail about possible SCFs and appear to use nominal stresses. To be clear these limitations of DELs are recognized. In their analysis of low-frequency fatigue dynamics Sadeghi et al. found that their results were sensitive to the assumed slope $m=3$, $m=4$, or $m=5$ (Sadeghi et al., 2023; Sadeghi et al., 2022).

While DELs are a very popular metric to use when analyzing offshore wind support structure fatigue, damages have also been calculated directly with actual SN curves. Pacheco et al. used damage indices as the selected metric when studying fatigue on an onshore wind turbine tower (Pacheco et al., 2022). In their study Pacheco et al. compared the relative impact of some capacity assumptions such as the bin size used to sort the rainflow cycle counts and the curve used in the analysis, DNV vs Eurocode curves. In a follow up study Pacheco et al. continued using damage index as a metric to study the damage extrapolation at a wind farm level (Pacheco et al., 2023). Although capacity assumptions are often overlooked in the broader SHM and Digital Twin space valuable insight can be found by using test data from a real offshore wind turbine to interrogate the relationship between turbine fatigue demand and the testing used to generate the SN curve, see chapter 4.

5.1.4 Methodology

This work will dive into the process of selecting a weld of interest and the effects of capacity assumptions on the results of the fatigue damage analysis. First, the justification and selection process for the specific weld detail is provided as a part of the BIWF overview. Next, the most likely SCF for the weld is calculated to provide a sense of how the stresses are amplified. However, because true knowledge of the exact tolerances and profile of the weld are not known to the team, the SCF in the analysis will be treated as an adjustable variable to examine how assumptions about the capacity affect results.

This approach to weld selection and SCF calculation was selected for two reasons. First, as OWSS are designed to last for 25+ years it is not uncommon for them to be sold to different asset owners or to be managed by different teams over the course of their life. BIWF itself was sold by Deepwater Wind to Ørsted¹. As a result, this exercise in identifying possible welds of interest based on contract drawings and a design report is understood to provide accurate information. Second, as the OW industry focused more on the impacts of corrosion-fatigue damage on the lifespan of these structures, more work is available on the impacts of corrosion pits. For example, Shojai et al created probabilistic models to match the SCFs from corrosion pits created on scanned corroded surfaces (Shojai et al., 2022). In the event of a failure of the corrosion protection system of a structure, it is not implausible that an asset owner would want to apply some representation of pre-corrosion to their structure by increasing the SCF of a detail.

The impact of the SCF variable will be compared across the following areas:

1. Total damage measured over the course of a year.
2. Impact of potential coating failure in the Splash Zone and subsequent use of a free corrosion SN curve.
3. The proportion of fatigue damage accumulating from stress cycles below the fatigue limit.
4. Damage accumulation that is broken up by months or SCADA data.
5. The ability to convert damage equivalent loads back into damages.

5.2 BIWF Overview

Block Island Wind Farm (BIWF) is the first commercial offshore wind farm built in the US. It was built in state waters off the coast of Block Island, Rhode Island in 2016 and consists of 5, 6 MW wind turbines supported by jacket structures (Hines et al., 2023). It was instrumented in 2021 with ten

¹ <https://orsted.com/en/company-announcement-list/2018/10/1819975>. Accessed on March 30, 2025.

accelerometers spread across five levels of the tower and four strain gauges installed at the base of the tower. No monitoring equipment was installed underwater.

Since gauges were installed at BIWF, several papers have been published about the structure. Simulations of the turbine structure were used to measure the sensitivity of modal parameters to environmental and operational conditions (Partovi-Mehr et al., 2023). Similar work was also done to measure modal parameters based on the data collected (Song et al., 2023). Partovi-Mehr et al applied modal expansion techniques on the BIWF jacket structure to estimate strains on the jacket based on the data collected (Partovi-Mehr et al., 2024). However, these results could not be validated because no strain gauges were able to be installed underwater on the jacket. BIWF data has also been used to study relationships between wakes and power production (Shid-Moosavi et al., 2025). This robust dataset has been useful for various research questions.

5.2.1 Selected Nodes

In Figure 49, node five is a jacket node that was analyzed in a previous fatigue analysis of BIWF (Partovi-Mehr et al., 2024). Node 5 is in the splash zone and has a total of 3 tubular welds, see figure 4. In addition to these tubular welds, each node is near a change in leg diameter (1.701 m to 1.625 m) and thickness (50.8 mm to 12.7 mm). *Figure 50* shows the weld detail being used at butt welds where the wall thickness and diameters change.

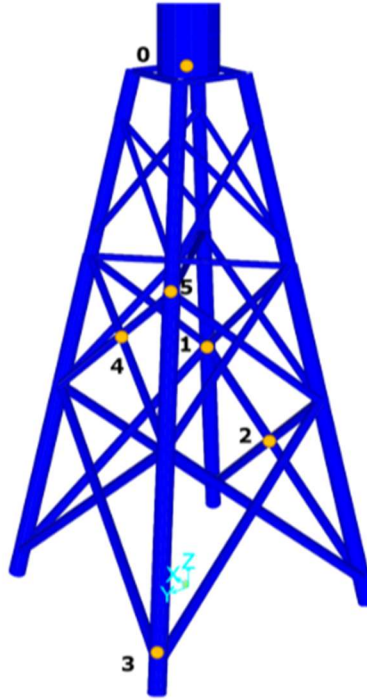
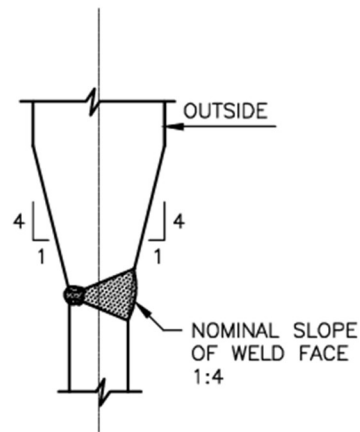


Figure 49 Model of BIWF Jacket (From (Partovi-Mehr et al., 2024))



WALL & DIAMETER CHANGE DETAIL

Figure 50 Image of Weld Detail (From Engineering Drawings)

5.2.2 Stresses and Weld Detail Selection

Revisiting the two papers about modal expansion for offshore wind jacket structures, the modal expansion method does not perform as well on the braces in the jacket (Augustyn et al., 2021; Henkel et

al. 2020). In their previous work on BIWF, Partovi-Mehr et al found that the weld at the brace had a very long (functionally infinite) fatigue life (Partovi-Mehr et al., 2024). It is not possible to validate this outlier result because there are no actual strain gauges on the jacket. Since modal expansion has a track record of issues with braces, and this result cannot be validated separately, it will not be the focus of this work. Instead, this paper will focus on the strains on the leg, which generally show a better fit in previous work on simulations and showed a meaningful amount of damage in the previous fatigue work on BIWF.

There are two primary options for weld details on legs at node 5. First there is the weld where the leg changes diameter and thickness, Figure 5, that appears to be a D-class butt weld per DNV RP c203 because it is a butt weld made from both sides (DNV, 2016). The SCF for this weld is relatively simple to analyze because it can be estimated using section 3.3.7 of DNV RP c203.

In addition to the D-class butt weld, there are also several tubular welds at node 5. These are more difficult to analyze for a few reasons. According to DNV-RP-C203, the first step to properly estimate the hot spot stresses is to classify the welds as T, Y, or K welds. However, the weld classification depends on the forces in the braces which as stated earlier are not fully trusted. While a visual assessment of the drawings suggests that node 1 contains two K type welds and node 5 contains two Y class welds, it is possible that the strains measured on the braces for this work are less accurate than strains on the legs.

Calculating the SCF of the tubular welds is further complicated by the fact that the typical Efthymiou equations used for jackets are intended for loading driven primarily by the braces (DNV, 2016). Previous work from Partovi-Mehr et al. has shown significant stress in the leg (i.e., chord) (Partovi-Mehr et al., 2024). According DNV RP c203 when there are significant dynamic stresses in the axial direction of the chord, the axial stress in the chord should be “increased by an SCF of 1.20 in addition to hot spot stress at the crown toe and heel” (DNV, 2016). This adds another layer of uncertainty to any estimate of the SCFs for the tubular welds.

Finally, the last challenge is the design of the leg itself. At both nodes there is a pile within the jacket leg and grout is injected into the annulus between the pile and the jacket. While DNV RP c203 has guidance on how the grout can be implemented into the existing equations via an effective chord thickness, the impact of grout on tubular connections is an area of active research (Liang et al., 2024).

Because the tubular welds are better handled by future work with a hybrid modeling approach that uses a detailed finite element model to estimate the SCF, this work focuses on the DNV-RP-c203, D-class butt-weld. This is the same weld class often used for unground circumferential welds in offshore wind monopiles.

5.2.3 Corrosion Conditions

Looking at the past work from Partovi-Mehr et al. node 5 appears to be in the splash zone. As a weld in the splash zone, it provides the opportunity to include the effects of a period of free corrosion on the remaining life estimate for the structure.

5.2.4 Envelope of Possible SCFs

With the D-Class butt-weld selected, the range of potential SCFs needs to be defined for the analysis of fatigue damages. Section 3.3.7.3 in DNV-RP-C203 provides an equation to calculate the SCF at a thickness transition girth weld assuming the weld transition looks like Figure 51 with a 4:1 ratio on one side of the weld. It is important to note that the weld detail in Figure 51 does not match the actual weld detail on the jacket where there is a slope on both sides, Figure 50. While the weld details are not the same, this is the equation most appropriate for butt welds.

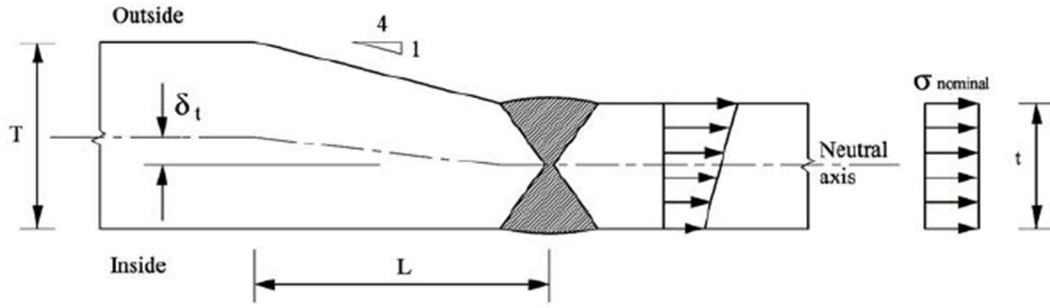


Figure 51 Butt-weld SCF Diagram from DNV-RP-C203

Equation 10 calculates the SCF and uses two calculated parameters α , Equation 11, and β , Equation

12. In addition to those calculated parameters there are three deltas: δ_m , δ_t , and δ_0 .

- δ_m represents the combination of different eccentricities out of roundness, concentricity, and eccentricity of the centers. The potential values for this will be discussed later.
- δ_t represents the eccentricity caused by differences in thickness between the tubulars and is calculated using Equation 14. Because the weld profile in the jacket is from both sides rather than, the one side change seen in Figure 6 two cases are presented. One with the calculated δ_t and one with $\delta_t = 0$ assuming that the two-sided profile change means there is no δ_t eccentricity.
- δ_0 represents the misalignment inherent in the S-N data used to make the curves and is calculated using Equation 13

$$SCF = 1 + \frac{6 * (\delta_t + \delta_m - \delta_0)}{t} * \frac{1}{1 + \left(\frac{T}{t}\right)^\beta} * e^{-\alpha} \quad \text{Equation 10}$$

$$\alpha = \frac{1.82 * L}{\sqrt{Dt}} * \frac{1}{1 + \left(\frac{T}{t}\right)^\beta} \quad \text{Equation 11}$$

$$\beta = 1.5 - \frac{1.0}{\log\left(\frac{D}{t}\right)} + \frac{3.0}{\left(\log\left(\frac{D}{t}\right)\right)^2} \quad \text{Equation 12}$$

$$\delta_0 = 0.05 * t \quad \text{Equation 13}$$

$$\delta_t = \frac{1}{2} * (T - t) \quad \text{Equation 14}$$

While δ_t and δ_0 have equations provided in section 3.3.7.3, there is no such equation for δ_m in DNV RP c203. Per the DNV-ST-0126, there is no equation for tolerances on girth welds, but it does state that fabrication tolerances should be as strict as possible to minimize the SCF (DNV, 2018). Line 4.17.7.1 states that tolerances should comply with DNV OS C401 chapter 2 section 6 (DNV, 2024). Within chapter 2, section 6 of C401 figure 3 provides tolerance equations for special, primary, and secondary levels of welds. At this time, the team decided that the butt weld could be considered a primary or special weld meaning δ_m has two possible options. The maximum tolerance allowed according to the table is 4 mm.

$$\text{Special: } \delta_m = 0.10 * t \quad \text{Equation 15}$$

$$\text{Primary: } \delta_m = 0.15 * t \quad \text{Equation 16}$$

Based on these inputs the two calculated options for the SCF of this butt-weld are 1.76 for primary and 1.74 for secondary. The potential range for the SCF is 1.69 if $\delta_m = 0$ or 1.84 if $\delta_m = 4 \text{ mm}$. In their thesis work, Heshmati modeled a weld with similar D/t, 120, and T/t, 4, ratios and found the SCF to be 1.650 (Heshmati, 2016). This would seem to indicate that the equations from DNV RP c203 were used appropriately here to find a range from 1.69-1.84. If $\delta_t = 0$ the results change dramatically and the highest SCF is 1.13.

While these equations provide a starting point to get a sense of the possible SCFs, this work seeks to examine how sensitive fatigue damage results are to SCFs. To accomplish this, the SCF will be treated as a variable to assess sensitivity. Table 12 presents the SCFs used in this analysis with case 3 representing the most likely scenario according to this paper's analysis.

Table 12 SCFs used on BIWF Study

	General SCFs to Use for Sensitivity Study				
	Nominal	Case 1	Case 2	Case 3	Case 4
D-Curve	1	1.25	1.5	1.75	2

5.2.5 Thickness Effect Discussion

As mentioned in chapter 4 the thickness effect is widely seen as conservative based on the testing seen in the literature. The equation for the SN curve is repeated below to show that the thickness adjustment is composed of three variables t , t_{reff} , and k where t_{reff} , and k come from DNV-RP-c203, and t is dependent on the thickness of the plate at the weld. Looking at Equation 17 the thickness adjustment functionally acts as an additional stress concentration factor.

$$\log(N) = \log(\bar{a}) - m \log \left(\Delta \sigma \left(\frac{t}{t_{\text{reff}}} \right)^k \right) \quad \text{Equation 17}$$

In this case for a D curve butt-weld $t_{\text{reff}} = 25$ mm and $k = 0.2$. If a tubular weld was selected instead of a butt-weld $t_{\text{reff}} = 16$ mm and $k = 0.25$. In this case the butt-weld has an actual thickness of $t = 12.7$ mm while the tubular thickness has an actual thickness of $t = 50.8$ mm. Because the thickness of the butt-weld is below 25 mm the thickness effect here is a multiplier of 1. While it is not included in the analysis here the thickness effect for the tubular weld would be an SCF equivalent to 1.41.

5.3 Results and Discussion

[The following section is redacted pending approval from our industry partner.]

5.4 Conclusions

This work takes real world observations from one year of operating data of BIWF and uses them to investigate the sensitivity of fatigue damage to the application of capacity assumptions here simplified as the stress concentration factor. It is important to recall the series of assumptions and factors that may limit the utility of these observations:

1. The work is based on previous modal expansion done by Partovi-Mehr et al on the BIWF jacket structure. While these results appear to have captured the dynamics of the structure, there is no underwater strain gauge data available to fully confirm the results. It is possible that the results in this work may be biased by the modal expansion method.

2. This work chose to examine the butt welds on the jacket legs to manage the scope of the work and avoid added complexity from possible asymmetric loading of the braces, impacts of grout on the stress concentration of tubulars, and possible multi-axial fatigue effects. Future work could model the jacket nodes and use multiscale models as has been seen in literature.
3. Even when very aggressive SCFs were applied to the butt welds, the remaining useful fatigue lives estimated by this work are still higher than those expected in the design report.

Despite these caveats, the purpose of this work was to investigate how much capacity assumptions matter when using fatigue damage as a metric to investigate relationships with environmental conditions or to inform future fatigue testing. The following observations were made in this context:

1. Overall fatigue damage measurement is highly sensitive to SCF with a difference of over an order of magnitude as the SCF increases.
2. At minimum half of the damage measured came from below the fatigue limit at $1E7$ number of cycles and where there is greater uncertainty about the position of the SN curve. When nominal stresses are analyzed, the relative importance of this region of the SN curve increases.
3. SCF assumptions do appear to have some impact on the proportion of damage that comes from specific months and operating conditions. It is unclear how critical these slight differences may be when fatigue is used as a metric for investigating other relationships.

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Chapter 6 Synthesis of Chapters 3, 4, & 5

This chapter is intended to synthesize the work done in the previous three chapters and highlight specific details of interest on offshore wind monopiles from a corrosion-fatigue perspective. It is written in a more conversational tone and includes opinions from the author in which I use first person language. This is covered in this way because much of the information provided in this chapter is either already established in the literature in previous chapters or an opinion I have developed through my own reading and discussions with designers over five-plus years at Tufts. This chapter is framed to identify research gaps and areas for future work related to details on offshore wind monopiles. It is broken up into four sections. First, there is a general review discussing different parts of the support structure, corrosion zones, and curve selection. Second, specific parts of the support structure are highlighted and advice on possible capacity assumptions is provided. Third, special cases and options for future work are discussed. Finally, my own framework/guidance for fatigue analysis is provided as conclusions.

6.1 General Review

Figure 52 shows a typical monopile foundation made up of 3 sections: a monopile, a transition piece, and a tower. There are also five corrosion zones defined in Figure 52: the atmospheric zone, the splash zone, the submerged zone, the mud zone, and the buried zone. Details defining the splash zone based on metocean data can be found in Figure 53, taken from Section 4.3.2 of DNVGL-RP-0416 (DNV, 2016). In Figure 53, the top of the splash zone is defined by the high still water level (HSWL) plus the significant wave height of a wave with a 1-year recurrence period and the lower part of the splash zone is defined by the lowest seawater level minus the trough depth of a 1-year recurrence wave. In Figure 42 these are labeled D and E respectively.

Technically speaking, in DNV-RP-0416, the mud zone is not defined as a distinct corrosion zone. Instead, it is a part of the larger submerged zone. I have added it to Figure 52 because the mud zone is

delineated in another standard from VGB/BAW (VGB PowerTech, 2018). While it does not define the mud zone DNV-RP-0416 does recommend combining coating and cathodic protection around the mudline because it can be an area of the monopile without much water circulation. This can lead to low oxygen conditions and promote the growth of microorganisms that can be particularly bad for microbiologically induced corrosion (MIC). In my opinion, this potential for increased risk of MIC justifies the distinction.

As discussed previously, there are three categories of SN curves available from DNV-RP-c203 covering three environmental conditions: in-air, cathodic protection, and free corrosion. In general, I would expect the atmospheric zone and splash zones to be protected by a coating. When the steel is coated, an in-air curve is used. While the atmospheric zone was not a part of my work, failures in the coating on the tower were not an issue that I have heard discussed. In the splash zone, the general rule of thumb is a fifteen-to-twenty-year lifespan for coatings assuming a NORSOK 7B coating (NORSOK, 1999). After the coating in the splash zone fails, it is assumed to be in a state of free corrosion. For the submerged, mud, and buried zones, the cathodic protection system would be expected to last for the entire life of the structure making the cathodic protection curve appropriate for 25-30 years. The free corrosion curve should be used for any conditions with no functional corrosion protection.

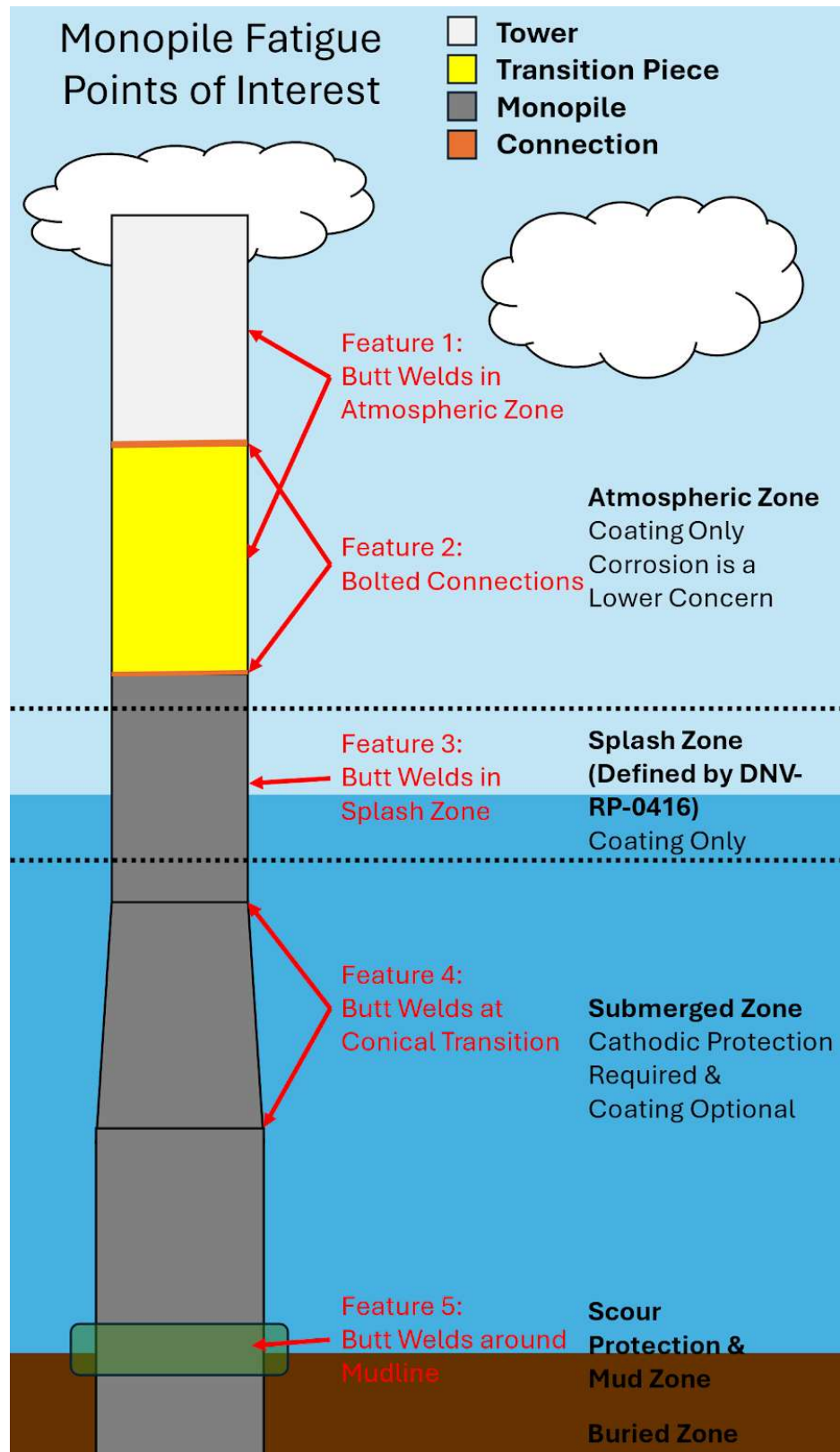
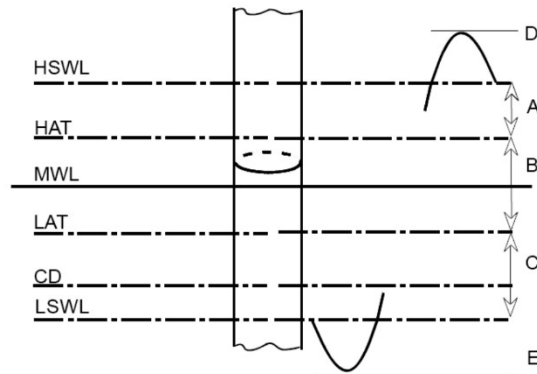


Figure 52 Diagram of Monopile with Corrosion-Fatigue Hotspots



HSWL highest still water level
HAT highest astronomical tide
MWL mean water level
LAT lowest astronomical tide
CD chart datum (often equal to LAT)
LSWL lowest still water level
A positive storm surge
B tidal range
C negative storm surge
D maximum crest elevation
E minimum trough elevation

Figure 4-2 Schematic representation of levels acc. to IEC 61400-3

Figure 53 Diagram Defining Splash Zone (from DNV-RP-C203)

Figure 54 taken from DNV-RP-c203 shows the in-air SN curves where each SN curve is classified by a letter, i.e. D. DNV-RP-c203 defines the weld classes in Appendix A. My work has focused on the circumferential butt welds that make up the cans of the monopile and transition pieces. These welds are at the spacing of the cans, which is about every 5 meters for monopiles and transition pieces. In the as-welded condition, these are typically D-class welds. If the welds are ground down to be flat, the C1 curve can be used. I do not have any insight about weld grinding other than it is expensive and avoided when possible. A ground weld may indicate a detail where fatigue is a concern. While I have no personal experience with towers, I assume they are also constructed with circumferential butt welds. For base metal, the B1 curve could be used, but in my experience, the base metal never controls from a fatigue perspective.

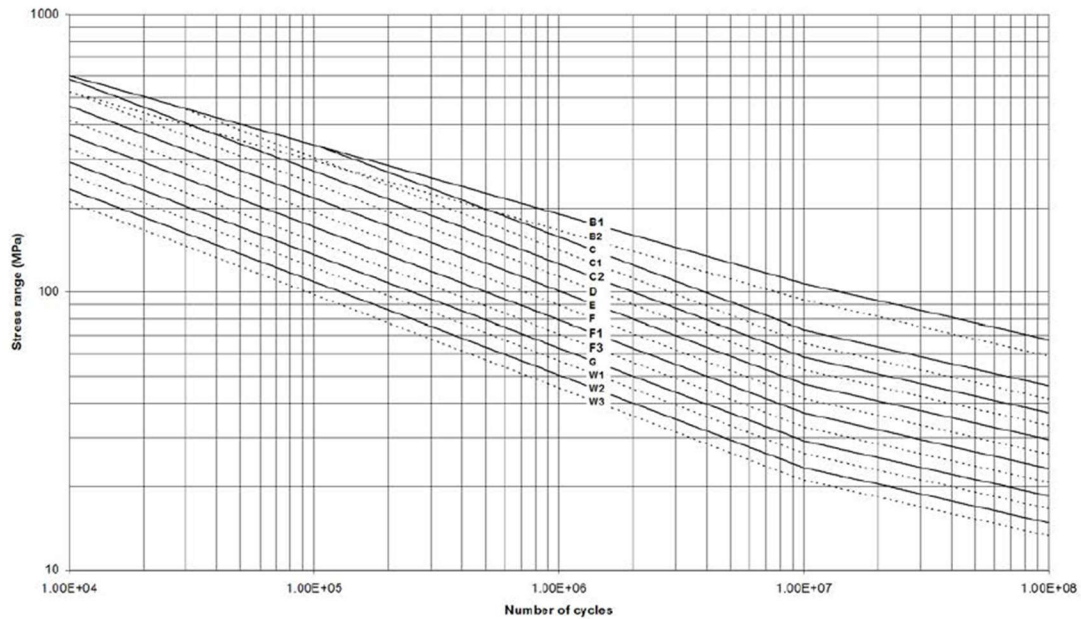


Figure 54 In-Air SN Curves (from DNV-RP-C203)

6.2 Specific Sections of Support Structure

In addition to these general rules, I have identified five categories of features to discuss:

1. The first feature is butt-welds in the atmospheric zone. From a corrosion-fatigue perspective these are uninteresting. One would not expect a high degree of corrosion risk and my limited work calculating fatigue damages at these locations have not produced any results likely to control a design. However, even though these are not the most interesting welds to examine, the tower is the cheapest and easiest place to have strain gauges. This is why modal expansion was used in chapter 5 to extrapolate the strains to the leg. If one wanted to examine an interesting detail on the tower that is not a weld stresses around the door is a topic that has been researched (Kang et al., 2021).
2. The second feature is the connections between the transition piece and tower or the monopile and transition piece. While I was unable to find specific statistics on the breakdown of these connection types, the bolted connection seems to be the primary design in modern monopile

foundations. Another recent innovation of the past few years has been the growth of TP-less monopiles where the tower is bolted directly to the monopile without any transition piece. My work has focused on welds, so this connection is a bit out of scope. If I were to approach a fatigue analysis here, I would break it up into two parts. First, what is the fatigue life of a weld at the flange? Second, what is the fatigue life of the bolts themselves? Based on conversations I had at an industry conference; the performance of these bolted connections is an area of active focus for the industry. This is supported by some references focused on this connection (Mehmanparast et al., 2020; Seidel, 2010; Seidel et al., 2021; Weijtjens et al., 2021). However, these references tend to focus on bolt pre-tensioning rather than fatigue. There is also some past work on bolt fatigue by a lab in Germany (Schaumann & Eichstädt, 2015). Studying fatigue at the connections could be an interesting, but time-consuming, effort.

3. The third feature, butt-welds in the splash zone, is the most interesting from a corrosion standpoint because assuming a 25–30-year lifespan, it is likely that a free corrosion curve will be used for some portion of the remaining life estimate. The main challenge here is how to define coating durability and failure. As discussed in chapters 2 and 3, coating performance can depend more on the specific application quality for a project or foundation rather than some inherent property of the coating. Also, coating failure is not a pure binary for the whole splash zone. For example, there could be local mechanical damage over some base metal, but the weld could still have intact coating over it. In this theoretical example, failure may not even be catastrophic to the remaining useful life of the structure because the base metal fatigue performance is much better than the weld. The splash zone butt-welds are an area where the coating durability could be treated as a random variable in the context of a larger structural reliability analysis.
4. The fourth feature, butt-welds at the conical transitions, is the most interesting part of the monopile from a stress concentration factor standpoint. The SCF for a generic butt weld is

discussed in chapter 5 and more information can be found in DNV-RP-C203 section “3.3.7 Tubular Butt Weld Connections”. However, as monopiles have been used for deeper waters and larger turbines, their diameters have increased up to 10 meters at the mudline. To reduce the magnitude of the wave loads and ensure the monopile diameter is the same as the diameter of the tower base, many monopiles have a section where the walls are angled. The butt welds where this angle occurs have a significantly higher stress concentration factor. The equations for this weld detail can be found in DNV-RP-C203 section “3.3.9 Stress Concentration for Conical Transitions” (DNV GL, 2016). The details and background of these equations are beyond the scope of my work.

5. The last category, butt-welds at the mudline, are similar to butt-welds in the splash zone except they are protected by cathodic protection. This means the cathodic protection curve would be used instead of the in-air curve. Assuming the cathodic protection system is designed properly, and MIC does not occur, there is no reason to expect free corrosion at this level.

6.3 Special Cases and Future Work

The details listed above provide a good starting point for fatigue damage analysis. The goal should first be to identify a detail that is interesting from a fatigue perspective. After that is done there are a number of adjustments to the capacity assumptions that could stress test how sensitive the detail is to uncertainties on the fatigue capacity side.

6.3.1 Dealing with Minor/Moderate Corrosion

One major question when using SN curves for corrosion-fatigue damage calculations is what happens when steel is temporarily subjected to free corrosion conditions. One way this can happen is a lag between monopile installation and the activation of the cathodic protection system. This is true for both galvanic and impressed current cathodic protection. This does not affect the splash zone, but would

be relevant in the submerged, mud, and buried zones. Another way this could occur is due to a failure in the cathodic protection system. As discussed in chapter 3, some designers have expressed concerns about the reliability of impressed current cathodic protection systems and a fatigue damage projection could estimate the severity of reliability issues by assuming some periods of free corrosion over the life of the structure.

One final motive to examine the interactions between intermittent corrosion and fatigue damage is the risk of MIC. While there have not been any documented examples of MIC causing issues for offshore wind platforms, it is something that could have an effect. Lab testing from Jansen et al has suggested that MIC can reduce the effectiveness of cathodic protection under certain conditions even under very negative potentials (Jansen et al., 2014; Jansen, Gerritse, et al., 2017; Jansen, van Burgel, et al., 2017). There is also some evidence that the industry is being proactive about MIC in the form of a technical note produced by Fugro for the Netherlands Enterprise Agency by Fugro (Fugro Engineers B.V., 2017). This note was one part of a larger geotechnical site assessment of an offshore wind energy zone. While the risk of MIC is not conclusive it could justify the study of sensitive welds near the mudline are to corrosion-fatigue damage in the event that they are not protected by coating and cathodic protection.

These situations highlight a major limitation of SN curve analysis. There are only three cases for environmental conditions. There is no clear guidance for a temporary period of corrosion followed by cathodic protection or intermittent corrosion caused by a faulty ICCP system or MIC. The simplest way to handle this would be to follow DNV-RP-c203 guidance that states that if the weld is ground free, corrosion can be accounted for by downgrading the SN curve by one class. However, there are also other more complicated options.

One way to handle inconsistent corrosion conditions would be to apply a corrosion pit model to the surface first and then do the fatigue analysis with the changed SCF. For example, Shojai et al. have

developed a model trained on laser scanned specimens taken from the North Sea (Shojai et al., 2022). One limit to such an approach is that not many corrosion pit models consider the impact on the whole weld they focus on just the SCF from the pits. In fatigue testing of pre-corroded specimens, Gkatzogiannis et al. observed an unexpected result when the pre-corroded specimen had a longer fatigue life than the corroded specimen because the corrosion smoothed over the weld profile/bump (Gkatzogiannis et al., 2019, 2021; Weinert et al., 2021). If one wanted to use even more complex models, there are several proposed multiscale models for corrosion fatigue modeling, but they are beyond the scope of this work (Larrosa et al., 2018).

6.3.2 Additional Fatigue Testing

As discussed in chapter 4, corrosion-fatigue testing is very difficult in general and particularly difficult for SN curve testing. Chapter 5 then discusses how SN curves are the most popular damage model to use because they are simple. The reason why SN curve testing is particularly difficult is because it is often accelerated by increasing the frequency of testing to about 5 Hz. For example, one of the studies in Zhao's database paper is a 2016 thesis from Olafsson which contained 19 butt welded specimens tested under cathodic protection conditions (Zhao, 2021). However, a deeper examination of the thesis from Olafsson shows that the cathodic protection tests were done at 8 Hz (Ólafsson, 2016). Now, it has been established in LEFM testing that corrosion-fatigue damage is sensitive to the testing frequency and intuition would indicate that since corrosion is a time dependent process corrosion-fatigue damage under SN testing would also be sensitive to frequency. Olafsson recognizes this in their thesis and states:

“The test series is not representing the expected corrosion process relating to offshore structures and the corresponding wave loading. Instead, the test series is comparing the influences of the testing environment.” (Ólafsson, 2016) **page 133**

Ideally under these uncertain conditions the existing literature would give some indication about how stability of the environmental reduction factor (ERF) for SN curves to frequency changes. As a reminder, Table 6 did show that testing frequency varied across programs in the 1980s. However, there are very few butt-welds tested in that dataset and the results are quite scattered, see Figure 40. Thus, it is difficult to say with any certainty if the Olafsson testing under cathodic protection conditions captures the kind of material behavior expected at offshore wind foundation weld details.

Even if more constant amplitude corrosion-fatigue testing was done to better define the $m=3$ section of the SN curve, Chapter 5 showed that much of the cumulative damage came from stresses below the fatigue limit, at least 50%. This means that the second half of the SN curve associated with the Haibach adjustment from $m = 3$ to $m = 5$ is an important part of the curve to get right for that kind of detail on an offshore wind foundation. Additional constant amplitude testing could change the position of the fatigue limit (i.e. the knee point of the SN curve), but it cannot provide insight about the second half of the SN curve associated with variable amplitude testing. There are two possible ways to address the second half of the SN curve. In a pre-print article, the author of DNV-RP-c203 proposes different parameters for the second half of the SN curve for thick D class welds based on a linear elastic fracture mechanics approach (Lotsberg, 2024).

The second option would be to initiate a new test program that combines two testing techniques currently being used for other purposes. In Germany a lab group that wanted to examine the beneficial effects of high frequency machine impacting on welds developed a protocol where specimens undergo accelerated pre-corrosion and then tested in-air (Gkatzogiannis et al., 2019). This process while imperfect does capture one important aspect of the corrosion-fatigue interaction SCFs at corrosion pits. The second method is Gassner curves. Gassner curves are a different form of SN curve that adjusts the typical SN curve (i.e. Wohler-Curve) according to the spectrum of load sequences seen in the rainflow count (Facchinetti, 2018). Gassner curves do not fully account for the impact of variable amplitude

loading but they recognize that the number and magnitude of load cycles above the fatigue limit matters. Gassner curves have been commonly used in the automotive industry and have been used in the context of corrosion-fatigue of aluminum (Lagoda & Sonsino, 2004; Sonsino, 2007, 2022). There is also a recent example of them being used to inform a testing program for offshore wind turbine foundations in the Baltic Sea which must accommodate ice loads (Braun et al., 2022). A testing program that combined these two processes to conduct variable amplitude testing on pre-corroded specimens may provide additional insight into the second half of the SN curve as well as information about crack initiation.

6.4 Framework/Guidance for Fatigue Damage Analysis

Rather than specific recommendations the key findings from chapter 6 are a generalized framework/guide for corrosion-fatigue analysis of weld details using SN curves, which consists of the following steps.

1. Obtain a stress time series either at a point of interest from either a strain gauge, modal expansion technique, or other techniques.
2. Apply a stress concentration factor (SCF) that is appropriate for the point of interest. If it is a butt weld with no significant thickness change an SCF of 1 is likely close enough. If there is a significant thickness change, the SCF may be somewhere between 1-1.5, but most likely around 1.2. If it is at a conical transition weld, the SCF is likely somewhere between 1.5-2 and 2 would be a reasonable initial guess. More accurate SCFs could be calculated using the equations from DNV-RP-c203 or from a detailed FEA analysis.
3. Run the rainflow count.
4. Calculate damage equivalent stresses (DES) using a slope of $m = 5$ and the equation from Sadeghi et al. As shown in chapter 5 the DES will likely overestimate the fatigue damage to some

extent, but it is a very helpful metric to compare across different elevations of a monopile to find key areas of interest.

5. Select an SN curve for the analysis. A circumferential butt weld on a monopile is typically a D-class weld (per DNV documents). If the weld is ground, it can be taken as a C1 class weld. If the weld is in the submerged zone or lower, using the cathodic protection curve for the full life of the structure is reasonable/close enough. If the weld is in the splash zone, use the in-air curve for 15-20 years and then extrapolate using the free corrosion curve for the remaining life.
6. Apply the bi-linear SN curve to the rainflow count of the stress time series. The DES can be directly converted to a damage index but based on chapter 5 this will be a conservative estimate of the projected fatigue damage.
 - a. Note: The rainflow count will also provide the user with mean stress. Following DNV-RP-C203 stress cycles that occur with a mean stress that is in compression can be reduced in magnitude. In this work none of the welds have been close to failing due to fatigue so this adjustment has been ignored making the estimates more conservative.

Primary Contributions of PhD Research

A generalized framework/guide for fatigue analysis was developed after practicing fatigue damage calculations on multiple different structures. The gaps between the way fatigue demands are calculated by modelers and digital twin builders versus how fatigue testing is done, and SN curves are developed and displayed to emphasize the need for new testing combining pre-corroded specimens and variable amplitude loading. No other groups have examined how the stress histograms interact with the bilinear SN curves.

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Chapter 7 Sustainable OW Foundations and NID

Offshore Wind (OW) development in the United States is primarily focused along the Atlantic Coastal Shelf stretching from the Carolinas up to Massachusetts. This region contains almost all the OW lease areas in the U.S. because strong wind resources paired with relatively shallow water depths allow well-established fixed foundation technologies to be used (see figure 1) (BOEM, 2022). Recent OW growth has already led to \$36B of investments into port infrastructure across the US according to an industry report (Oceantic Network, 2024). However, as OW grows it is important to figure out how it fits into pre-existing economy.

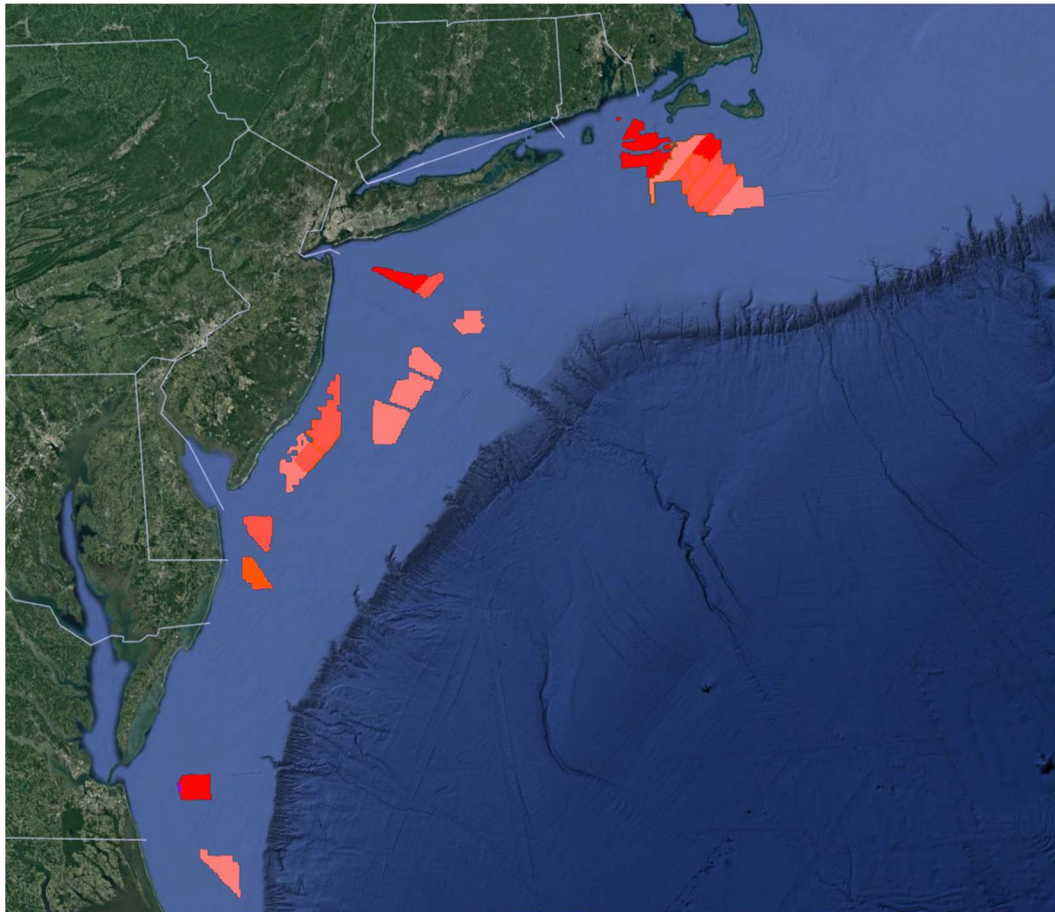


Figure 55 Map of East Coast Atlantic Shelf with Lease Areas

OW development along the East Coast must coexist alongside a major seafood industry with strong cultural and economic ties to coastal communities (Colburn, 2016). Commercial fisheries operating out of New England and mid-Atlantic ports generate \$2B/year in landings revenues, or about 40% of the national total, and the seafood industry in this region is estimated to support, directly or indirectly, nearly 350K jobs with total sales impacts of over \$45B/year (UD Department of Commerce, 2023). Even before OW development started in this region, these fisheries were at risk due to the combined impacts of a changing climate and anthropogenic effects such as overfishing and local pollution (Heck et al., 2020). Compared to the North Sea, which had an established oil and gas industry prior to the development of OW, the East Coast of the U.S. does not have a history of offshore structures. Creative thinking and proactive planning are needed to coordinate the coexistence of the seafood industry and the new offshore energy industry.

In addition to specific conflicts with fisheries, local communities have been skeptical of OW. For example, Smythe et al. used an energy justice framework to investigate the experience of members of coastal communities in the Northeast; they found that local “participants experienced the federal government-led planning and permitting process, in itself, as the problem” and that “the primacy of local communities was inadequately recognized” (Smythe et al., 2025). This finding mirrors prior work from Susskind et al. that used a database of renewable energy project opposition to highlight how procedural complexity is a risk factor that affects public opposition to projects (Susskind et al., 2022). In addition to concerns about procedure and a general backlash to renewable energy, OW also faces a nascent network of opponents made up of a mix of local groups enabled by formal think tanks that provide an “information subsidy” (Slevin et al., 2025). While there is no silver bullet for acceptance of OW energy, engagement with local stakeholders to build a positive vision about the role of OW in the ocean could counteract general concerns about industrialization.

One key theme uniting the challenges with the fishing industry and general public is that OW energy in the US needs to be incorporated into the larger Blue Economy that encompasses all ocean activity. In their 2016 article “The New Blue Economy: the Future of Sustainability,” Spalding introduces the term the *New Blue Economy* and says it is important to have a well-defined scope with specific sectors and metrics so that its growth can be tracked in a way that is “understandable and usable by decision-makers at varying scales” (Spalding, 2016). Spalding’s paper breaks the new blue economy into traditional sectors (i.e. Recreational Fishing, Commercial Fishing, Open Pen Aquaculture, Coastal Tourism, etc.), new industry sectors (i.e., Renewable Energy, Remediation/Restoration, Blue Technology, etc.), and a *New Blue Economy* subsector that synthesizes the traditional and new industry sectors and focuses on sustainability and biodiversity impacts. The *New Blue Economy* provides an excellent framework to balance OW energy development, sustainable seafood production, and ecosystem preservation.

Work has already begun in Europe to balance energy, seafood, and the environment. Over 25 GW of OW capacity has been connected to the European grid in the past decade (Ramirez et al., 2023). Energy production will always be the primary driver for OW farms, but because of the massive scale of the projects, subtle changes can have major impacts downstream. Stakeholders in the European seas are looking for ways to maximize the positive impacts of OW projects beyond clean energy generation. With the right policies and knowledge, OW investment can be leveraged to build the *New Blue Economy*.

This work introduces a framework called Nature Inclusive Offshore Wind Farms (NIOWFs) to describe how OW development fits into the *New Blue Economy* in the context of the U.S. East Coast. *Figure 56* illustrates how NIOWFs cut across three key pillars of the *New Blue Economy*: energy production (i.e. new industry sectors), economic development (i.e. traditional sectors) and the *New Blue Economy* subsector represented here as ecosystem management.

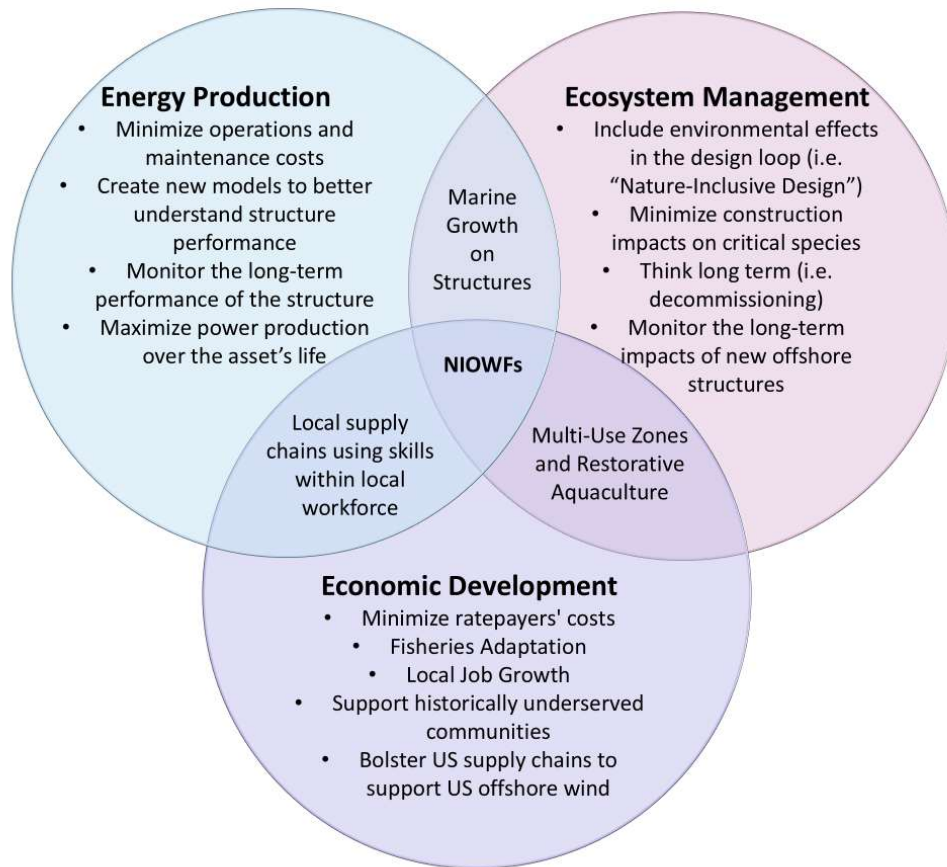


Figure 56 The 3 E's of the New Blue Economy and NIOWFs

Methodology

This review was supported in part by an award (#2315558) from the U.S. National Science Foundation (NSF) on an Engine Development project titled "MOCEAN: Accelerating a Just Energy Transition while Nurturing Healthy Ocean and New Blue Economies through Innovative Offshore Wind Farms". MOCEAN (Mission is the OCEAN) is a broad-based group united in the view that the development of the U.S. OW energy resource presents a large and critically important opportunity to the future prosperity and health of many coastal communities and ecosystems. This work has included discussions at three workshops and a review of over 100 articles and reports to develop a framework that supports the MOCEAN mission. The intent of this review is to provide a broad overview of an array

of efforts ranging from marine spatial planning (MSP) policy, nature inclusive design (NID) features, and multi-use pilot projects to outline a vision for the NIOWF framework. In addition to the literature review, at points this paper summarizes discussions from a kick-off meeting for the MOCEAN initiative in January of 2024. These sections are clearly defined in the paragraphs and sections that pull from discussions at this meeting. These sections are not used to make declarative statements, but rather to emphasize certain key questions and research gaps.

7.1 Work and Perspectives from Europe

Because the European OW industry is mature with over 25 GW of installed capacity, ocean stakeholders from all over Europe have experience managing conflicts between ocean stakeholders. Managing the ocean is a complex problem requiring cooperation between governments, developers, fisheries, marine scientists, NGOs, and coastal communities. While the US does not have the same scale of OW development there is no reason why the US cannot learn from the European experience.

In Europe, conflict management can be broken into three broad categories marine spatial planning (MSP), multi-use zones, and nature inclusive design (NID). All three fields of research and practice balance positive ocean stewardship with blue economy development. They are complementary fields but approach the problem from different perspectives. Marine spatial planning research is framed from the perspective of the government and focuses on policy and stakeholder engagement. Multi-use research focused on developing early pilot projects and identifying partners to help commercialize new ideas. NID is at the nexus of marine biology and engineering design to create features that have a net positive impact on the environment. Figure 57 uses the common analogy of a three-legged stool to show how each field is critical to the development of NIOWFs.

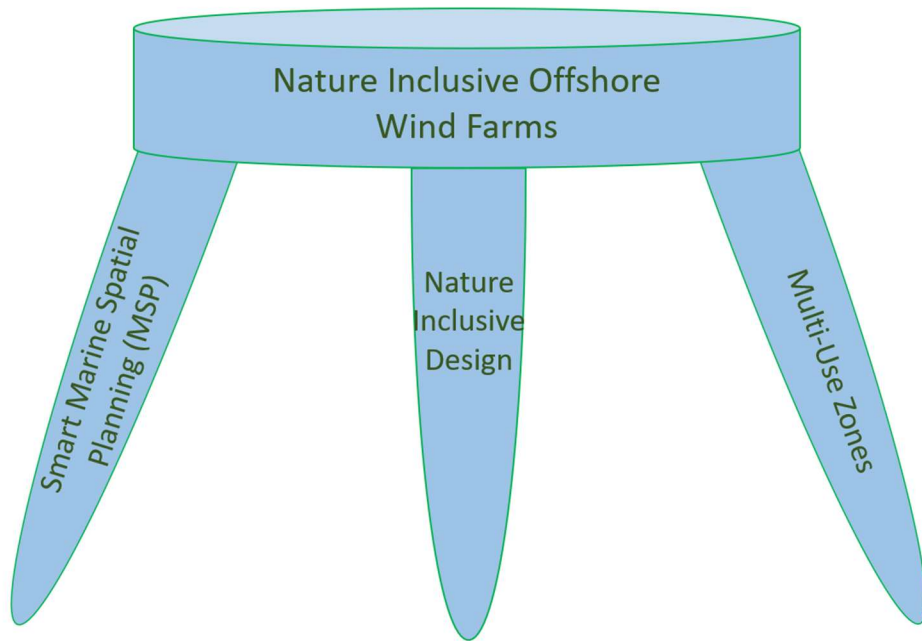


Figure 57 NIOWF Stool Diagram

7.1.1 Marine Spatial Planning

Marine Spatial Planning (**MSP**) is defined by the IOC-UNESCO as “A public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives that have been specified through a political process” (IOC-UNESCO/European Commission, 2022). MSP was initially used in the 1980s to describe efforts towards marine conservation, but recently the focus has shifted to conflicts among activities (e.g. among marine conservation, renewable energy, and fishing activities) in crowded ocean spaces such as the North Sea (Frazao Santos et al., 2019). Academic publishing on MSP boomed after an IOC-UNESCO workshop on the topic in 2006, and the European Union (EU) has an MSP policy directive. A website was launched in 2016 to share relevant reports and government planning documents called the EU MSP Platform (EU MSP Platform, 2023).

MSP policies in Europe overlap with other EU goals focused on preserving biodiversity and deploying clean energy. In the North Sea, where there are many countries sharing a relatively small patch of ocean, there has been a lot of tension. According to a 2022 report focused on MSP policy interactions with EU Green Deal the four most common conflicts for MSP are: nature conservation versus fisheries, nature conservation versus extractive activities, nature conservation versus offshore renewable energy development, and offshore renewable energy development versus fisheries (van den Burg et al., 2022). These relationships underscore the trade-offs inherent to MSP. Offshore renewable energy (ORE) makes up two of the four most common conflicts. MSP is a critical part of managing these conflicts by allocating space for each activity. The ability to maximize the positive impact of OW depends on a study foundation of smart MSP.

The growing role of ORE, particularly OW, has become a major theme in the MSP community globally as well. In the UN Global Compact Ocean Stewardship Coalition published the “Roadmap to Integrate Clean Offshore Renewable Energy into Climate-Smart Marine Spatial Planning” two of their key recommendations relate to biodiversity and multi-use zones. Key recommendation number seven identifies the need to “[s]trengthen the links between [Offshore Renewable Energy] ORE and biodiversity protection/restoration to maximize climate mitigation effects” while key recommendation number eight says that entities need to “[e]xplore synergistic multi-use combinations that can speed up the transition to low-carbon and climate-resilient economies” (UN Global Compact, 2021). This roadmap highlights the role of MSP.

Climate change is one of many risks to marine biodiversity that requires balancing. On one hand, deployment of ORE can reduce CO₂ emissions and help mitigate climate change effects. However, ORE deployment will affect the local marine environment and if these effects are not properly considered, they can have a net negative impact on total marine biodiversity. MSP is a policy tool that can directly

shape the environmental and economic tradeoffs at the government level. If it is designed well, it carefully considers input from ocean stakeholders.

7.1.2 Multi-Use OW Energy Areas

The Multi-Use in European Seas (MUSES) project arose to support the European Union Marine Spatial Planning Directive and develop Ocean Multi-Use Action Plan (Schultz-Zehden et al., 2018). The MUSES project examined a total of nine opportunities for multi-use, four of which included offshore wind farms (OWFs): OWF & Tourism, OWF & Fisheries, and OWF & Aquaculture, OWF & Marine Renewable Energy. MUSES defined multi-use as the following:

“[Multi-use] is an umbrella term that covers a multitude of use combinations in the marine realm and represents a radical change from the concept of exclusive resource rights to the inclusive sharing of resources by one or more users” (Schultz-Zehden et al., 2018).

After the conclusion of the MUSES project in 2018, the Multi-Use offshore platforms demonstrators for boosting cost-effective and eco-friendly production in sustainable marine activities (aka UNITED) began in 2020 (About UNITED). While MUSES focused on stakeholder engagement and paper studies, the UNITED project took the next step by deploying five pilots. The first pilot in Germany combined blue mussels, seaweed and offshore energy. The second pilot in the Netherlands combined seaweed and floating solar energy. The third pilot in Belgium combined OW, oyster restoration, and seaweed cultivation. The fourth pilot in Denmark combined OW and tourism. Finally, a fifth pilot in Greece combined aquaculture and tourism (UNITED, 2023). This project ended and has been succeeded by the ULTFARMS project in 2023 (ULTFARMS, 2025).

Outside of these two major projects, several research papers have been published on the topic of multi-use zones. Co-location of OW farms and fisheries activity were one of the multi-use opportunities examined as a part of the MUSES project. A stakeholder analysis for both German and Scottish OW farms examined the different barriers to multi-use (Schupp et al., 2012). Similar work was

published using a SWOT (Strength, Weaknesses, Opportunities, & Threats) analysis for mariculture and OW [37]. Much of the early work done on the potential of multi-use zones is also summarized in the MUSES reports (Nassar et al., 2020; Bocci et al., 2019).

The most complete synthesis of MSP and multi-use principles comes from the Symbiosis Inclusive Design (SID) work introduced in a roadmap published by a Dutch OW consortium called GROW. GROW published a report titled “Advancing Multi-Use in Offshore Wind Farms” that breaks up the synergetic opportunities of OW farms into three main pillars: food, nature, and energy (GROW, 2023). This breakdown for SID recognizes food production, energy production, and protection of the natural world as three key drivers for ocean use and stewardship much like the three E’s for MOCEAN listed in Figure 56.

In addition to these specific reports and projects actively piloting ideas, there is research available about the interactions between offshore wind farms in Europe and other ocean industries. The North Sea is home to almost 80% of Europe’s total OW capacity (Ramirez et al., 2023). Consequently, much of the cutting-edge work on the interactions between OW farms and the environment come from the North Sea. For example, report commissioned by the European Commission about the effects of OW on fishing and aquaculture summarizes the different strategies between Belgium, Denmark, Germany, Netherlands, Sweden, and the United Kingdom (Van Hoey et al., 2021). This report is referenced later to compare Europe with the U.S.

The definition of multi-use also opens the door for a very expansive view of an ocean “user”. If one includes nature as an ocean “user” environmental protection and restoration becomes a part of the multi-use umbrella. The idea that the environment is an ocean stakeholder is already seen in the Nordic energy research report on coexistence (Nordic Energy Research, 2023). If the idea of multi-use is expanded to include the environment as an ocean user, then nature inclusive design (NID) fits neatly into the same framework.

7.1.3 NID in Europe

NID in Europe focuses on a relatively narrow band of design decisions made within an offshore wind farm tied to environmental impact. According to a catalogue of NID features published by Wageningen University:

“NID refers to options that can be integrated in or added to the design of an OW infrastructure to create a suitable habitat for native species (or communities) whose natural habitat has been degraded or reduced” (Hermans et al., 2020).

This definition of NID is common in Europe and is also used by the Nordic Energy report on coexistence (Hermans et al., 2020). The broad definition NIOWFs used by MOCEAN is different from this specific definition of NID in Europe. While MOCEAN views economic effects as a critical component to its vision for the Blue Economy, NID in Europe is focused on environmental impact.

In addition to this definition of NID the private sector uses the phrase “net positive impact” to describe work focused on attracting and improving marine growth in offshore wind farms. Orsted, Vattenfall, Equinor, and Iberdrola all have set ambitious goals that their projects will have a net positive impact on biodiversity by 2030 (Orsted, 2023; Equinor, 2024; Iberdrola, 2024; Vattenfall, 2023). These companies have taken a variety of approaches to achieve this goal. As examples, Iberdrola recently gave an award for a start-up competition focused on integrating nature into the design of OW farms (“Spoor wins...”, 2023) and Orsted is piloting a project to use OW jacket structures in Taiwan to restore native corals (Orsted, 2023).

One careful note about NID and net positive impact research is that it is additive and does not replace the existing mitigation hierarchy used for offshore wind projects. Figure 58 taken from a summary report of a symposium focused on net positive biodiversity impacts for offshore wind shows how avoidance, minimization, and restoration still form the foundation of environmental impact assessment (Jedele et al., 2023). The additional conservation efforts cover the NID features that seek to make the project “net positive” on the local environment. While the definition of NID does not

specifically account for the foundation of the mitigation hierarchy, it is inherently intertwined when stakeholders talk about offshore wind and net positive impact. NID efforts need to be built on top of robust marine science and monitoring programs that form the basis of the mitigation hierarchy.

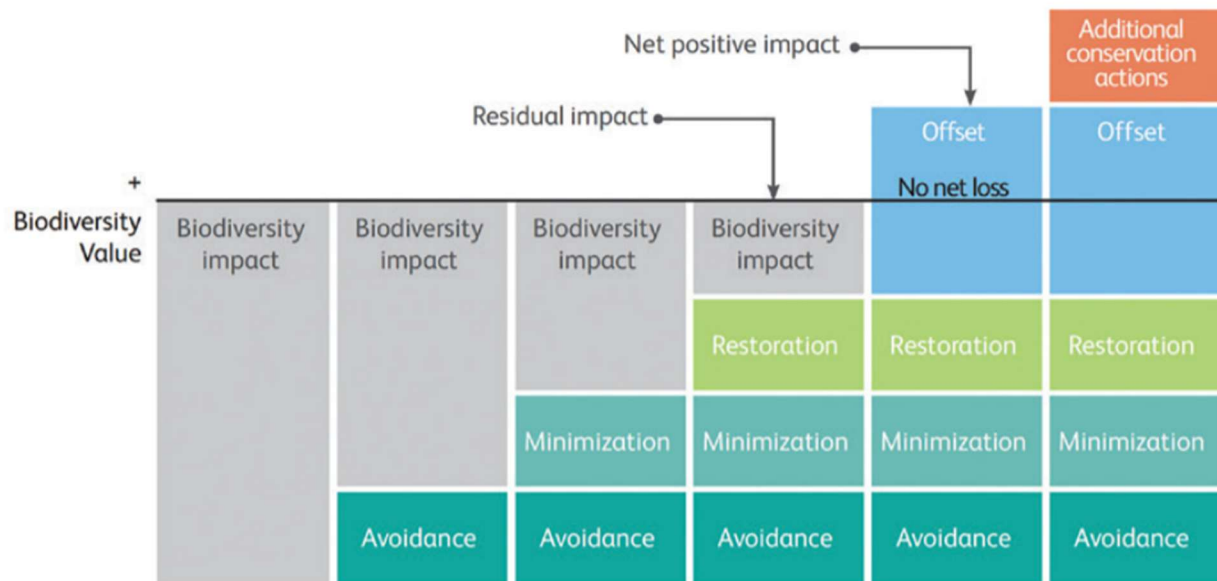


Figure 58 The Role of Net Positive Impact on Mitigation Hierarchy (from (Jedele et al., 2023))

Several NID projects have been piloted in the Netherlands. One example would be efforts to restore oyster reefs overlap with efforts to create new wind energy zones. In 2022, the Dutch Ministry for Agriculture, Nature, and Food Quality commissioned a report that examined the suitability for flat oyster restoration efforts within wind farm zones (van Duren et al., 2022). This report follows a previous pilot project in Dutch OW farms (Sas et al., 2018). The Rich North Sea (de Rijke Noord zee), a private research organization, formed by Natuur & Milieu, and The North Sea Foundation (Stichting De Noordzee) has been a critical supporter of these efforts such as a project that supported artificial reef design within OW farms with Blauwwind (Stassen, 2023). Another NGO called the Offshore Coalition for Energy and Nature (OCEAN) combines the efforts of multiple organizations involved in offshore wind to apply NID principles in the North Sea and Mediterranean Sea at regional levels (OCEAN, 2025).

In addition to these specific studies and pilot projects, NID has been included in the OW procurement process. The Netherlands recently held a tender (aka OW auction) where NID criteria accounted for half of the total 200 points available for one of the OW zones (Netherlands Enterprise Agency, 2022). This is a critical development since prior to this there was not a precedent to have incentives within the OW procurement process to promote NID. Policy support for NID in the tender process is one of the recommendations made by the Nordic Energy Research report indicating additional interest in the subject (Nordic Energy Research, 2023). Without supportive policy, the potential of NID will not be fulfilled.

7.2 OW Development in the US

The first U.S. OW farm, BIWF, was installed in 2016 with only five turbines. Unlike the North Sea, the eastern seaboard of the U.S. does not have a history of offshore infrastructure from oil and gas development that could be monitored and provide a record of data on interactions between the structure and marine environment in the region. Despite the relative lack of direct experience and data in the U.S., environmental impacts of OW have been a focus of U.S. research programs. This research has focused on generating reports to identify research gaps and on active monitoring programs for the handful of U.S. OW installations (BOEM, 2024).

7.2.1 Introduction to U.S. System

Before comparing the OW ecosystems in the EU and the U.S., a brief overview of the U.S. system is needed. In the U.S., all planned commercial OW projects are greater than three nautical miles off the U.S. coastline, placing them in federal waters. Projects in federal waters are regulated by the U.S. Department of the Interior (DOI), specifically the Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE). BOEM is the primary regulator for projects up until the completion of construction, while BSEE is the primary regulator for projects during operation

through decommissioning. BOEM starts the process for OW by identifying lease areas as a part of the planning and analysis phase all the way on the left side in Figure 59 (BOEM, 2023).



Figure 59 BOEM Regulatory Roadmap (Taken from BOEM Website)

Figure 59 shows the steps required to get a wind farm built in federal waters, but for a project to be viable developers also need to sell the power that the wind farm is expected to generate through a procurement process which varies by state. For example, in Massachusetts, the Department of Energy Resources, in concert with local Massachusetts utility companies, solicit proposals for long term OW energy contracts to follow state law Section 83c (Mass Department of Energy Resources, 2023). Connecticut, Rhode Island, New York, New Jersey, and Maryland each have their own competitive bid process followed by an award for power purchase with details varying from state to state. Projects also need to plug into the grid with cables that traverse state waters, so developers coordinate with state and local governments to get permits for the electrical transmission equipment. In Massachusetts, the electrical transmission equipment for Vineyard Wind 1 needed to be approved by the Massachusetts Energy Facilities Siting Board (EFSB) (Sedor et al., 2019).

There are exceptions to this process. For example, the first U.S. OW farm, BIWF, is unique because it was developed in Rhode Island state waters. In Virginia, Coastal Virginia Offshore Wind

(CVOW) is being built by the vertically integrated utility company (Dominion) instead of a competitive bid process (Dominion, 2024).

7.2.2 US Marine Spatial Planning

In the U.S. there is no equivalent national program to the European MSP directive. The closest thing would be an executive order from 2010 that separated the EEZ (Exclusive Economic Zone) into nine different regions and created a framework for MSP, but this executive order was replaced by a different framework in 2018; only two of the nine ocean regions received federal approval for plans, the Northeast and mid-Atlantic regions (Ehler, 2021). The Northeast Regional Ocean Council (NROC) and Mid-Atlantic Regional Council on the Ocean (MARCO) formed to foster collaboration across state and disciplinary boundaries so that these plans could be developed (MARCO About; NROC About). These councils still exist today and provide valuable services such as the northeast ocean data portal and mid-Atlantic data portal. NROC and MARCO also support the Regional Wildlife Science Collaborative (RWSC) for OW, an entity focused on “regional monitoring and research of wildlife and marine ecosystems that supports the advancement of environmentally responsible and cost-efficient OW power development activities in U.S. Atlantic waters” (RWSC, 2025). In addition to these two regional plans, four states have an MSP plan established by state law: Oregon, Washington, Rhode Island, and Massachusetts.

While these marine spatial plans for the Northeast and mid-Atlantic are regionally relevant to fixed OW, they are also several years old. Some of their OW recommendations, such as coordinating with the Department of Defense, have already been implemented in databases maintained by NROC and MARCO. The 2023 lease selection processes for new wind energy areas in the Gulf of Maine are a better example of current MSP practices. A draft report of this analysis was released for comment in October 2023 (Randall et al. 2023). To create a draft wind energy area in the Gulf of Maine, BOEM used a gridded relative suitability analysis as a part of a Multi Criteria Decision Analysis (MCDA), dividing their criteria

into four main sub models given equal weights: (i) Natural & Cultural Resources, (ii) Industry & Operations, (iii) Fisheries, and (iv) Wind. The draft report itself has more details about how the sub models were built, but at a high level, it shows that identifying lease areas is an extensive mapping activity balancing the needs of varied stakeholders. While selection of U.S. offshore wind sites may not be formally driven by MSP policy like in the EU, the mechanics of how OW lease areas are selected parallels the European MSP.

This lease identification process requires a combination of environmental, economic, and social data. The U.S. National Oceanographic and Atmospheric Administration (NOAA) is a key partner in this process. Specifically, the National Centers for Coastal Ocean Science (NCCOS) have helped build spatial models for the mid-Atlantic, Oregon, Gulf of Mexico, and Gulf of Maine ocean regions. Supporting sustainable development of ORE is one of the sub-categories of NOAA's strategic goal to strengthen established sectors of the blue economy (NCCOS, 2022). The NOAA strategic plan does not include procedures for multi-use zones, but it mentions that private companies will collect data during OW deployment that could support NOAA's science mission. The plan suggests that partnerships with industry players could help advance NOAA's mission.

7.2.3 Multi-Use Zones in the U.S.

The U.S. also does not have an equivalent to the MUSES project or the UNITED H2020 project. This is largely due to different regulatory environments and approaches to OW. Europe has stricter rules and regulations surrounding navigation within OW farms in Europe, motivating conversations around multi-use zones. In Belgium and the Netherlands, no navigation is allowed within 500 m of a wind farm area (Van Hoey et al., 2021), and in Germany safety rules are established after a wind farm is constructed, but fishing is “de facto” banned (Schupp et al., 2021). The United Kingdom is the only major country in Europe that allows fishing within OW farms (Van Hoey et al., 2021). Some of the interest in

multi-use research in Europe likely comes from the very strict baseline a lot of countries have regarding navigation within OW wind energy areas.

In contrast to many countries in Europe, the U.S. has no planned restrictions on fishing activities inside of wind farms. Fishing is currently allowed at Block Island Wind Farm, and there are no plans to restrict access (Webster et al., 2020). For the much larger Vineyard Wind 1 farm with 67 turbines, there are also no plans to restrict access for navigation or fishing activities (Bennett, 2023). However, being legally allowed to fish in an area does not necessarily fully maximize an area's utility / impacts. In the UK, surveys with fishermen found that although a small number returned to operate in wind farms, most did not, due to a perception of higher risk (Gray et al., 2016). Limited experience in the U.S. with BIWF has indicated the opposite, and BIWF has become an attractive fishing destination for recreational fishermen (Smythe et al., 2021). The BIWF experience provides some reasons to be optimistic with the caveat that there are still concerns about crowding and potential loss of access in the future. It could be argued that U.S. is ahead of Europe in multi-use zones because the U.S. approach to access would be defined as inherently multi-use in countries where navigation is restricted. However, the U.S. does not have the same projects such as MUSES or UNITED H2020 designed to actively identify barriers to multi-use.

The experience from the UK shows that real multi-use zones will need to be supported by proactive measures. Merely opening the OW energy areas to fishing does not mean they will be multi-use zones in practice. Currently the Responsible Offshore Science Alliance (ROSA) is acting as an important convenor of stakeholders. ROSA is a non-profit organization formed in 2019 to collaborate across a variety of stakeholders such as fisheries, OW developers, and experts in federal and state agencies to support research and decision making at the nexus of OW farms and fisheries (ROSA, 2025). ROSA is a critical organization for U.S. OW, but it does not have the level of resources of similar organizations in Europe.

In the U.S., there has been little discussion around co-locating aquaculture projects within OW farms. In 2022, the U.S. Department of Energy (DOE) Water Power Technologies Office (WPTO) and PNNL were involved in a report on ocean renewable energy and offshore aquaculture for the international energy agency (IEA) (Freeman, 2022). This report included OW as well as other ocean energy technologies such as wave energy and floating solar. Rather than focusing on the synergies that come from co-locating ocean activities, the report focused mostly on the potential for offshore renewable energy to supply power for offshore aquaculture.

The lack of interest in co-locating aquaculture with OW farms in the U.S. may be due to the nascent nature of the aquaculture industry in federal waters. In their review of the global aquaculture industry, Garlock *et al.* found that the growth rates for aquaculture in North America and Europe were the lowest in the world and that aquaculture in the U.S. shrank in the last decade (Garlock et al., 2020). In a 2016 review of the U.S. aquaculture market, Knapp and Rubino mention there are efforts in the U.S. to reverse this negative trend for aquaculture. According to NOAA's most recent strategic plan, one of the key outcomes for strengthening established sectors of the blue economy is to "create a national framework for sustainable and productive aquaculture" (NOAA, 2021). In addition to including aquaculture in their overall strategic plan, NOAA has published a strategic plan for aquaculture covering the years 2023-2028 and a guide to permitting aquaculture in the U.S. (NCCOS, 2022; NOAA, 2022). NOAA is not the sole permitting authority for aquaculture, but it plays an important role in coordinating efforts at the federal level. In addition to these reports by NOAA, the National Science and Technology Council Subcommittee on Aquaculture has published a plan to enhance regulatory efficiency and coordination among the relevant federal and local agencies (National Science and Technology Council Subcommittee on Aquaculture, 2022). Compared to OW where much of the coordination for permitting is handled by one federal agency BOEM, the process for offshore aquaculture in the U.S. is less streamlined. It is possible that the relatively new permitting process for marine aquaculture in federal

waters makes it a less attractive option for multi-use zones due to a higher permitting risk, but a more detailed analysis of the barriers such as the ones done in Europe for the MUSES project are needed in the U.S.

7.2.4 NID in the U.S.

While there has not been enough OW construction in the U.S. to have a broad experience with NID design features, there has been a significant focus on the potential environmental impact of OW farms. Because the Northeast U.S. does not have a history of offshore energy infrastructure, much of the current research discussion in the US has focused on fundamental issues like a lack of baseline marine data. It is fair to say that discussion in the US is further down the mitigation hierarchy with research focused on establishing the baselines and monitoring needed to support mitigation. As mentioned earlier, successful NID implementation requires firm foundation of mitigation.

Recognizing that the US is behind Europe in this regard there have been several research projects in the US to build this foundation. The U.S. Offshore Wind Synthesis of Environmental Effects Research (SEER) project, co-lead by the Pacific Northwest National Laboratory (PNNL) and National Renewable Energy Laboratory (NREL), is a large multi-year paper study of OW environmental effects in the U.S. (US Offshore Wind Synthesis of Environmental Effects Research, 2020). The SEER project has developed a database of relevant projects on Tethys as a part of their literature review, convened multiple workshops on specific environmental topics, and published a series of synthesis reports, and online materials. These reports cover the following seven main topics:

1. Bird and Bat Collisions
2. Vessel Collisions
3. Floating OW Cable Systems
4. Underwater Noise Effects

5. Effects on Fish Ecology
6. Electromagnetic Field Effects
7. Benthic Disturbances

In addition to paper studies and reviews, field work has been done on the limited number of OW assets in U.S. waters. The BOEM Realtime Opportunity for Development Environmental Observations (RODEO) project has monitored the five turbines at BIWF and two turbines at CVOW since 2015 and 2021 respectively. The RODEO monitoring focuses on a variety of topics including underwater noise, benthic/epifaunal effects, and sediment suspension/turbidity (BOEM, 2024).

The research into environmental effects of OW farms is only the start. Understanding this nexus of marine science, biology, and engineering creates a foundation for this knowledge to be put into practice. A technical report from The Nature Conservancy and INSPIRE Environmental was inspired by the Dutch NID catalogue and investigates opportunities for NID in wind farms off the U.S. East Coast rather than for the North Sea (The Nature Conservancy, 2021). Although the U.S. eastern Atlantic coastal shelf is similar to the North Sea in Europe, the two regions differ according to the Marine Ecoregions of the World (MEOWs) model commonly used to define ocean regions (Spalding et al., 2007). While the lessons from Europe have significant value for U.S. OW technologies and features should be adapted to the U.S. market not applied one to one.

7.3 Key Questions for US NIOWFs

The U.S. OW ecosystem has many of the pieces needed to develop NIOWFs. However, there are no active large-scale projects to coordinate stakeholders, support pilot projects, and understand the permitting requirements. Compared to European wind farms that have historically restricted access to their OW energy areas, the U.S. is in a good position to explore synergies between the fishing industry and OW. Aquaculture in U.S. federal waters is at an early stage of development but should also be

explored as a multi-use opportunity. There have been major efforts from organizations such as NOAA to explore opportunities in aquaculture, but these have mostly been occurred in parallel to discussions about OW deployment. Greater coordination is also needed in the U.S. to build NIOWFs with all three pillars of the *New Blue Economy*.

In addition to a general need for more resources and coordination, there are several key questions and barriers that need to be addressed. These questions cover a range of challenges including technical, environmental, social, and policy. Some can be partially answered using existing work in the U.S. or from projects in Europe. In many cases, the answers remain unknown and need to be developed in future work.

7.3.1 What incentives exist to promote NIOWFs in the U.S.?

Experience in Europe has displayed the importance of government policy and tender structures on the OW market. In the U.S., state governments have the most power over OW procurement. Table 13, adapted from research done by the Vermont Law and Graduate School, shows the breakdown of points for the most recent OW solicitation of each East Coast state (James et al., 2023). One key takeaway from Table 13 is the lack of consensus in the state procurement process. Apart from Maine, which only recently published a roadmap for OW in 2023, and Maryland, which starts its review with a qualitative assessment of non-price criteria to see which bids will get to be reviewed on price, every other state has a split of roughly 70/30 for price/non-price criteria. Connecticut and Rhode Island have a slightly higher focus on price at 75/25 but also make up a relatively small proportion of the overall OW market on the U.S. East Coast.

The non-price criteria in state requirements tend to focus on some combination of project viability, economic benefit, and impact on the environment and fisheries. However, these top-level categories can be misleading. For example, in New York, “quiet installation” methods and management

of installation noise fall under project viability rather than environmental impact. Many states also have some requirements for environmental monitoring built into their procurements. New York and Maryland both require public reporting on environmental monitoring efforts. New Jersey and Massachusetts have both added language in their recent solicitations incentivizing environmental monitoring and data transparency (James et al., 2023).

One major barrier to incentivizing nature inclusive OW via state policy is coordination across state boundaries because OW is not bound by state borders. South Fork Wind and Vineyard Wind 1 are only 32 nautical miles apart, but Vineyard Wind 1 is procured by Massachusetts while South Fork wind is procured by New York. One example of state coordination would be a memo of understanding (MOU) between Massachusetts, Rhode Island, and Connecticut that allowed for multi-state bids in their 2024 procurement process (“MA-RI-CT Memo”, 2023). OW transmission is a good example of a topic where the importance of regional coordination has been fully recognized. The recent DOE action plan for transmission in the Atlantic region is an example of the kind of regional perspective that is needed (US Department of Energy, 2023). Similar levels of coordination need to extend to conflicts with the environment and fisheries.

In addition to incentives during the state procurement process, there are opportunities at the federal level to shape the future of U.S. OW via the lease process. In 2022, BOEM used a Multi Factor Auction (MFA) format for its Carolina, California, and Gulf of Mexico lease areas (James et al., 2023). The MFA format incentivizes developers to invest money towards a certain policy goal in exchange for a non-cash credit that is added to their cash price during the auction. In previous auctions, BOEM has offered credit for domestic supply chain investments, workforce development, and money for a fisheries compensatory mitigation fund. Another credit was given for having a community benefits agreement (CBA) with local communities near the lease area. In a recent workshop on the potential for OW development to have a net positive effect on biodiversity, a panel of experts identified the MFA format

as a potential avenue to incentivize net positive impacts (Jedele et al., 2023). The panel recommended including a biodiversity criteria in the next auction for the Gulf of Maine. Even if it is too late for existing fixed OW projects to benefit, the multi-factor auction format can influence future projects.

The potential for policy incentives was also discussed during the MOCEAN meeting and the key questions and perspectives were brought up beyond what was found in the literature review. For example, the internal incentives and motivations that exist within the private sector because of their net positive biodiversity goals were flagged as an important driver of NID work in the United States. It was also discussed that adding complexity to the tender process for power procurement can raise the barrier of entry for new market participants. Participants stressed that any incentive structure for NIOWD should not inadvertently harm the existing OW market.

Table 13 Summary of State Procurement Policies

			Non-Price Criteria				
East Coast States	Key Procurement Organization	Price	Project Viability	Economic Benefits	Environment & Fisheries Impact	Requires Monitoring Research	Notes
New York	NYSERDA	70	10	20	N/A	Yes	Plans for "quiet " installations support Project Viability Score & all projects need an Environmental Mitigation Plan
New Jersey	NJBPU	70	N/A	15	15	Recommended	Demonstrate environmental net benefits & have Environmental Protection Plan (EPP)
Maryland	MDPSC	N/A	Qualitative assessment made before considering price			Reporting Required	Demonstrate environmental net benefits
Massachusetts	DOER & DPU	70	15	15		Recommended	Focus on Environmental Justice
Rhode Island	RIPUC	75	25			Part of EFMP	Requires an Environmental Impact and Fisheries Mitigation Plan (EFMP)
Connecticut	DEEP	75	25			No	Requires an Environmental Impact and Fisheries Mitigation Plan (EFMP)
Maine	MEPUC	N/A	N/A			N/A	Roadmap stresses importance of protdcting natural resources and the fishing industry

7.3.2 How could a focus on NIOWFs affect the identification of wind energy areas?

As described previously, the BOEM lease identification process balances the needs of different ocean users and analyzes trade-offs. Wind farm layout is one example of such a trade-off. OW farms in the U.S., such as Vineyard Wind 1, are laid out in a grid system with one nautical mile spacing to allow for navigation through the wind farm. This spacing allows for fishing activity inside of the OW area. However, this flexibility comes at a cost, as the layout cannot be fully optimized for power production. If fishers avoid navigating through OW farms, like in the UK, then U.S. policy is sacrificing optimal power production for an underutilized multi-use opportunity.

Distance to shore is another variable where there are trade-offs between visual impact and the potential for fishing utilization. In their survey of recreational fishermen, Smythe *et al.* noted that BIWF is unique because it is very close to shore and that the current trend for other U.S. OW projects, which are farther from shore to minimize visual impacts, may make them less attractive to recreational fishermen [60]. These kinds of trade-offs would have to be analyzed in an MSP process designed to consider multi-use opportunities when planning OW lease areas.

7.3.3 How might NIOWFs affect the public acceptance of OW projects?

As described in the introduction, OW projects are facing an increased degree of public concern. These concerns are driven in part by frustration with the processes around OW deployment and the sense that the system is unfair. For example, quantitative work focused on survey data about BIWF has been done to investigate how community members' underlying values and perception of the ocean affect public opinion of OW energy (Bidwell, 2017; Russell et al., 2021). Recently qualitative work from Smythe et al. used an environmental justice framework also identified fairness as a significant concern (Smythe et al., 2025). In addition to these research examples, the field of maritime and fisheries

anthropology could be a very helpful supplement to identify the needs of coastal communities. While maritime and fisheries anthropology have not been used extensively in OW related work, it has been used in the context of general marine management according to a recent review by Aswani (Aswani, 2020).

One goal of NIOWFs would be to allow OW industry members, other ocean users, and members of coastal communities to build a positive vision for the ocean together. One template for such a community would be recent work in the Netherlands focused on communities of practice [COPs] (Steins *et al.*, 2021). In their paper, Steins *et al.* utilize a pre-existing definition for a COP with three distinct qualities:

“[First] the domain: the identity of the COP is defined by a shared interest, [Second] the community: members of the COP pursue their interest in the domain through joint activities and discussions, help each other and share information, and [Third] the practice: members are practitioners who develop a shared practice.” – (Steins *et al.*, 2021)

In their paper, Stein *et al.* recognize that the community of practice in the North Sea (COPNS) is not a perfect COP because it was formed by the government of the Netherlands as a part of their marine spatial planning efforts and North Sea 2030 planning. Nevertheless, it serves as an example of how varying stakeholders can be brought together to exchange information and learn from one another. While surveys and anthropological studies can help identify key stakeholders and values to shape NIOWFs, some organization is needed to put these ideas into practice. Because initial research suggests that public frustration with OW projects is partially driven by procedural issues, a U.S. Atlantic COP could help ocean stakeholders come together to define a vision of the future of OW that also assuages fears of ocean industrialization.

7.3.4 How can the NIOWF Lens affect economic development?

Every state solicitation document also has a major focus on local economic development, see Table 13. These goals for economic development do not need to be mutually exclusive with goals for NIOWFs. The Nature Conservancy report on turbine reefs and OW comes with an appendix that lists eight different products that are produced in the U.S. and could be used for nature-based design (Nature Conservancy, 2021). NID features in particular may be a good option for providing local content in OW projects. Unlike other aspects of the OW system (e.g. monopile foundations, large offshore towers, blades, and nacelles) nature-based design features (e.g. NID scour protection) do not require the same highly specialized equipment and manufacturing facilities with direct port access. NID features are a part of the supply chain that could be a powerful aspect of local content and supply chain development.

In addition to producing components specifically for NID, NIOWFs could provide opportunities to support long-term jobs tied to the cumulative capacity of an OW build. One critique of OW as a tool for economic development is that many of the jobs are tied to the deployment rate rather than the cumulative capacity. In a 2022 workforce assessment, a team at NREL found that out of a total of 58,000 FTEs/year (jobs) by 2030 only about 2,300 FTEs/year would be in O&M, under 5% of total FTEs (Stefek et al., 2022). Figure 60 shows how non-O&M jobs (e.g. Manufacturing and Supply Chain, Ports and Staging, Maritime Construction and Development) are related to the annual deployment rate, assuming 100% domestic content. Over 80% of these jobs come from manufacturing and the supply chain. The supply chain workforce is not as elastic as other areas such as marine construction, so the relationship is not quite one-to-one, but the total FTEs appear to be somewhere between 50,000 and 70,000 jobs for an annual deployment pipeline between 4 GW and 6 GW. Figure 61 shows that cumulative installed capacity is closely tied to the total FTEs for operations and maintenance jobs in OW. These are the jobs that are expected for the 30-year life of the wind farm regardless of the deployment rate for new projects.

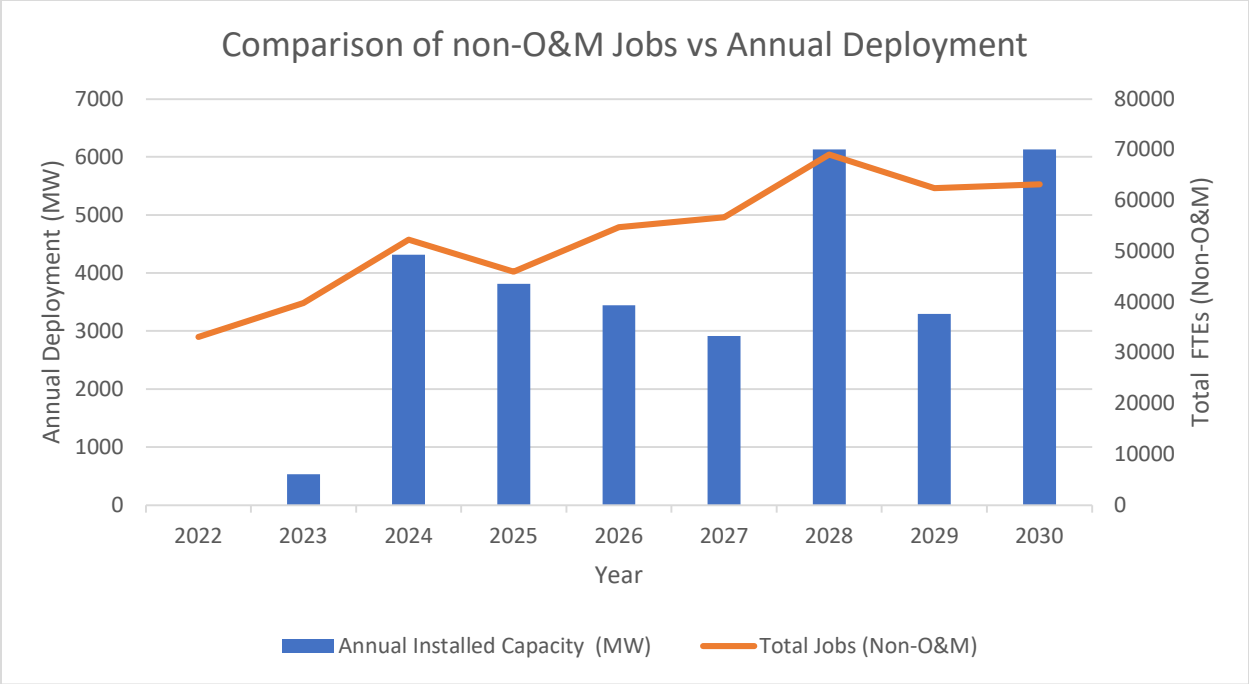


Figure 60 Relationship Between non-O&M Jobs and Annual Deployment (Based on Stefek Data for 100% Domestic Content (Stefek et al., 2022))

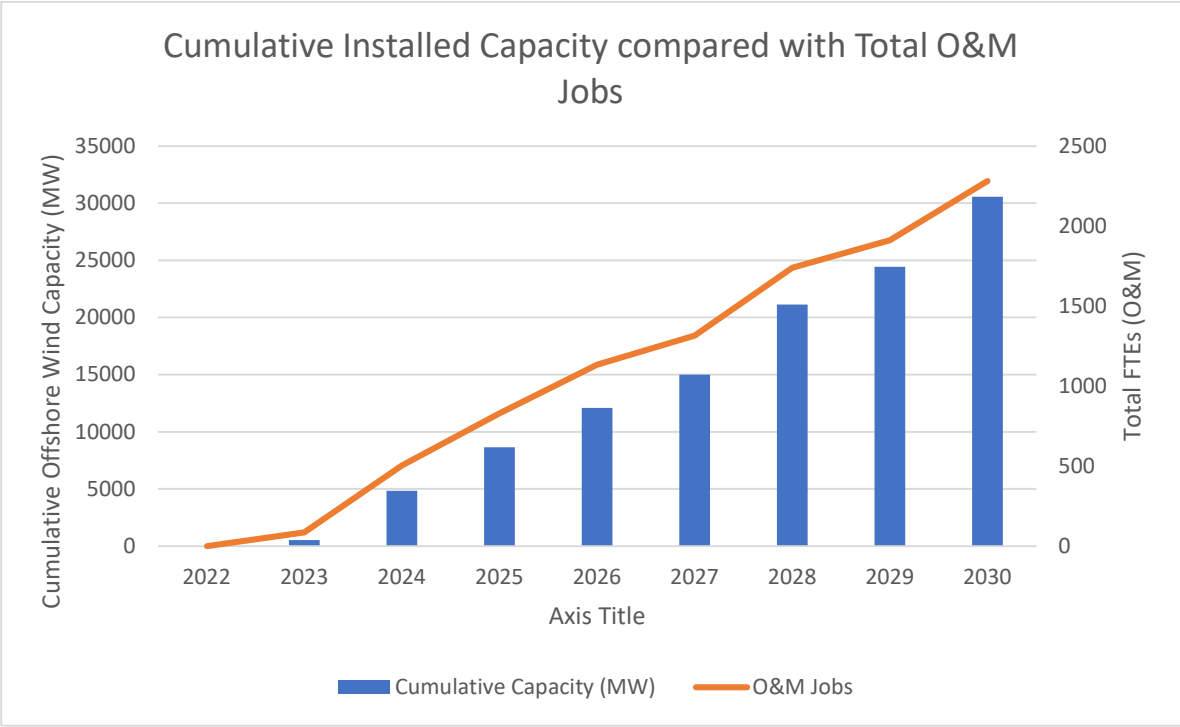


Figure 61 Relationship Between non-O&M Jobs and Cumulative Capacity (Based on Stefek Data for 100% Domestic Content (Stefek et al., 2022))

Proper project sequencing can create a robust pipeline of projects and ensure that the deployment jobs are stable, but job duration is a reasonable concern. From an equity standpoint, it is critical that OW provide sustainable work, not a cycle of booms and busts in coastal communities. Multi-use zones and support for NID can align with economic development to support an expanded, sustainable blue economy around OW. For example, in a paper on the five golden principles for marine reef restoration, Hostede *et al.* state that the fifth principle is active stakeholder engagement beyond activation. Hostede *et al.* emphasize that a marine reef restoration project is a 15–20-year commitment (Hofstede et al., 2023). The work to collect data, measure impacts of NID features, and maintain these structures can add to the “O&M jobs”. Beyond potential jobs for mariners and marine scientists in support of NID, a creative idea for multi-use zones would be to co-locate aquaculture within wind energy areas. Some researchers in the U.S. have examined the potential for blue mussel aquaculture in the U.S. Atlantic shelf (Mizuta et al., 2020; Mizuta et al., 2019). This could provide an additional layer of economic activity for local coastal communities.

While it does not tie directly back into a specific sector, a major topic at the MOCEAN workshop was the “workforce for the future blue economy”. This phrase was used to describe the idea that the introduction of the OW sector to the Atlantic shelf creates opportunities for a vast amount of data to be collected. At this time, the utility of this data and how available it will be is not clear but as time goes on it could become a valuable resource. One could imagine a market for prediction products and tools that utilize this data to support other commercial activities, such as fishing, or conservation goals. While this is still a very speculative idea, it was flagged as one worthy of further discussion and investigation.

7.3.5 Lease Lengths & Decommissioning

During the discussions at the MOCEAN workshop, lease lengths and decommissioning challenges were also discussed. The lease lengths for OW are typically around 25-30 years and the lease duration is

often attributed to a historical relic of the oil and gas industry. Obviously, the wind is an inexhaustible resource so participants pose the question of how a longer duration of lease activity may affect how projects are considered. This ties directly into NID features because seeing pieces of the infrastructure as beneficial to the local environment adds a layer of complexity to the decommissioning process. If an OW foundation is deemed to be useful as an artificial reef but is past its useful service life what is the appropriate action to take? These are the kinds of long-term questions that come up when OW structures are seen as an integral part of a new local marine seascape.

7.3.6 What research is needed to inform NIOWFs?

Multiple databases of research projects, research gaps, and existing technologies for environmental monitoring and mitigation have been identified to help find gaps in the existing research. These databases are generated by a variety of institutions including national labs (e.g. NREL and PNNL) as well as private organizations focused on OW (e.g. RWSC and ROSA). The abundance of databases and research in this space are indicative of the interest in the environmental effects of OW. However, it also means that a comparison of these different projects, organizations, and recommendations is needed to better understand the space.

The SEER project published a database of 219 recommendations for future research based on a review of over 800 documents (SEER Database, 2023). The SEER team created this database on behalf of the Regional Synthesis Working group. Figure 62 is made from a pivot table of the database and shows the number of recommendations for each receptor/taxon in the database. The total of the columns in Figure 62 is 607 because many research recommendations cut across multiple taxa. Recommendations related to fish and benthos are some of the most frequent with counts of 96 and 90 respectively. While the SEER research recommendations cover a wide range of taxa, fishes, benthos, and ecosystem/oceanographic processes are the most relevant for the underwater infrastructure associated

with NID. This prevalence of these taxa in the database indicates that a greater fundamental understanding is needed to inform the design of NID features.

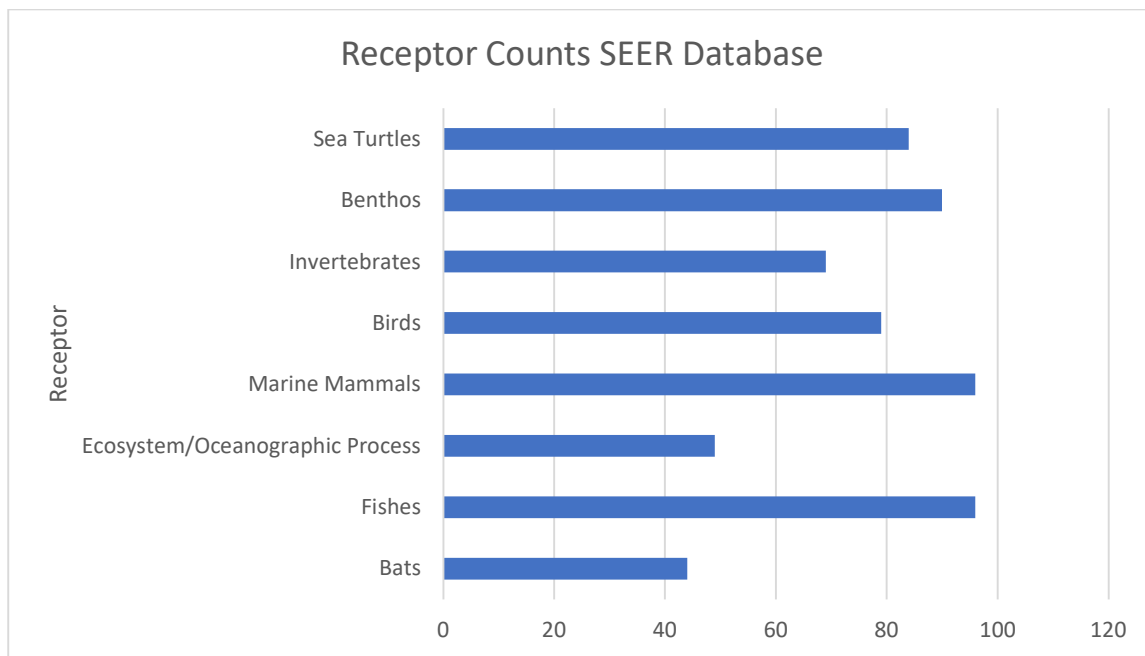


Figure 62 SEER Database Receptor Counts

Figure 63 breaks up the SEER recommendations into broad categories based on their stressor/topic and shows the totals for the receptors/taxa most relevant to NID features. The total of columns in Figure 63 is 349 not 219 because many research recommendations cut across multiple topics. Baselines, habitat change, noise, and technology/methods development stand out as the most common recommendation topics. Of these four baselines and habitat change are particularly important for the implementation of NID. Reliable baselines are needed to quantify the impact of NID features while habitat change is required to measure impacts and design NID features for intentional effects. Research on the impacts of noise are critical for mitigation, particularly pile driving noise, but it is generally less relevant for the kind of artificial reef effects examined as a part of NID. Finally, the technology/methods development topic cut across multiple categories because new technology and monitoring solutions will be needed for modern management of the oceans even beyond OW development.

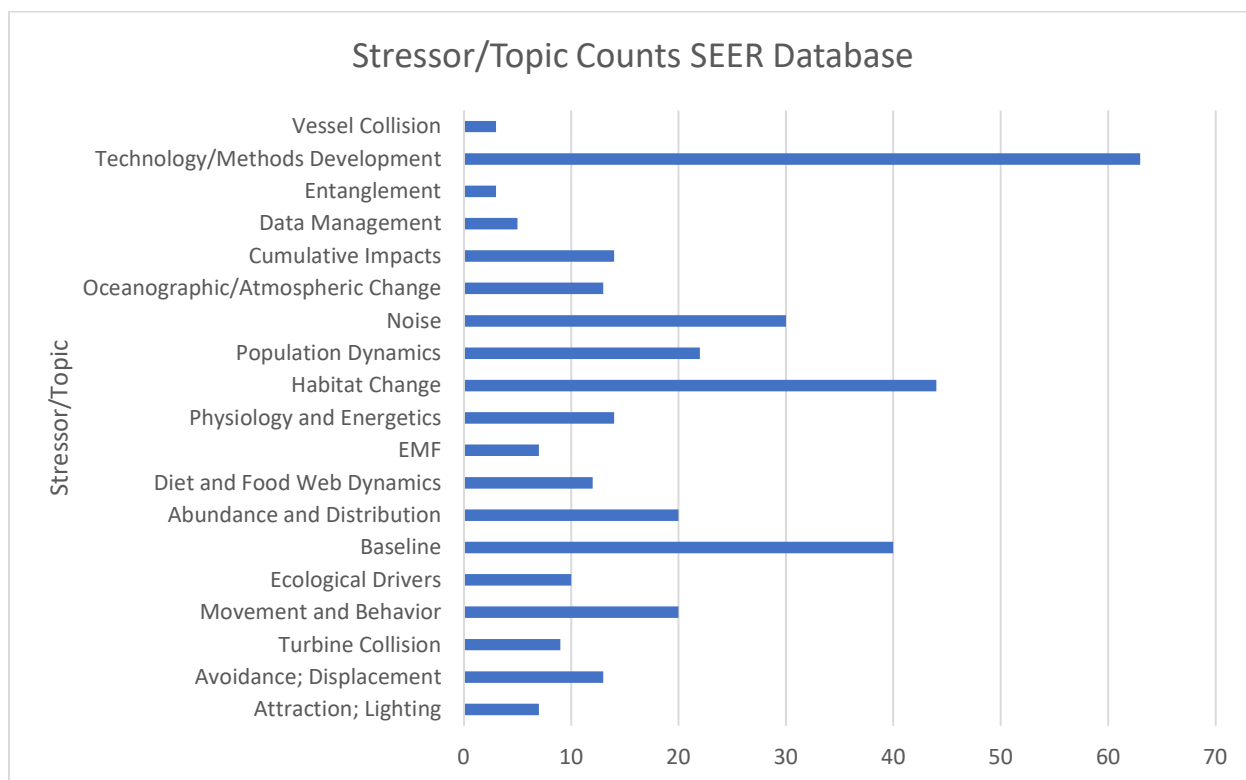


Figure 63 Synthesized Research by Topic for all Receptors

While the SEER Database is broadly concerned about environmental effects, it does not have a specific focus on fisheries. ROSA, the non-profit organization focused on the nexus of OW and fisheries, recently commissioned a database of relevant existing research programs and gaps that need to be addressed. The first draft of this database, named Fish FORWARD, was released alongside a user manual in 2022 (ROSA Database, 2022). Figure 64 and Figure 65 show the number of times that each research need appears in the database of 234 research recommendations as of November 28th, 2023. In this case, the totals for Figure 64 and Figure 65 both add up to 234 because the research needs category does not combine multiple topics into one listing. Null is the most common research need in Figure 65 because most research recommendations do not have two needs listed.

These two figures show that many of the research recommendations highlighted by the Fish FORWRD database broadly match the same Topics as the SEER database. While the specific wording may differ, “Species Distribution/Composition” is closely related to establishing “Baselines” and “Habitat Fragmentation/Modification” tie into “Habitat Change”. One major difference between the databases is that Fish FORWARD does not emphasize “sound/vibration impacts” nearly as much as the SEER database mentions “noise”. Part of this may be because the Fish FORWRD database only looks at Fish, Fisheries, and Other as research focuses. While noise is an important topic for all marine life, it is particularly relevant to marine mammals and BOEM released draft guidance for noise abatement in 2022 (BOEM, 2022). Another interesting difference between the SEER database and the Fish FORWRD database is the prevalence of electromagnetic forces (EMFs) in the Fish FORWRD database. In the fish FORWRD database, EMFs are more prevalent than noise for their research recommendations. This is a significant difference compared to the SEER database that does not even have EMFs in the top 5 most common topics for research recommendations. This may be due to a difference of opinion by experts in the field or due to the Fish FORWRD database’s focus on fisheries.

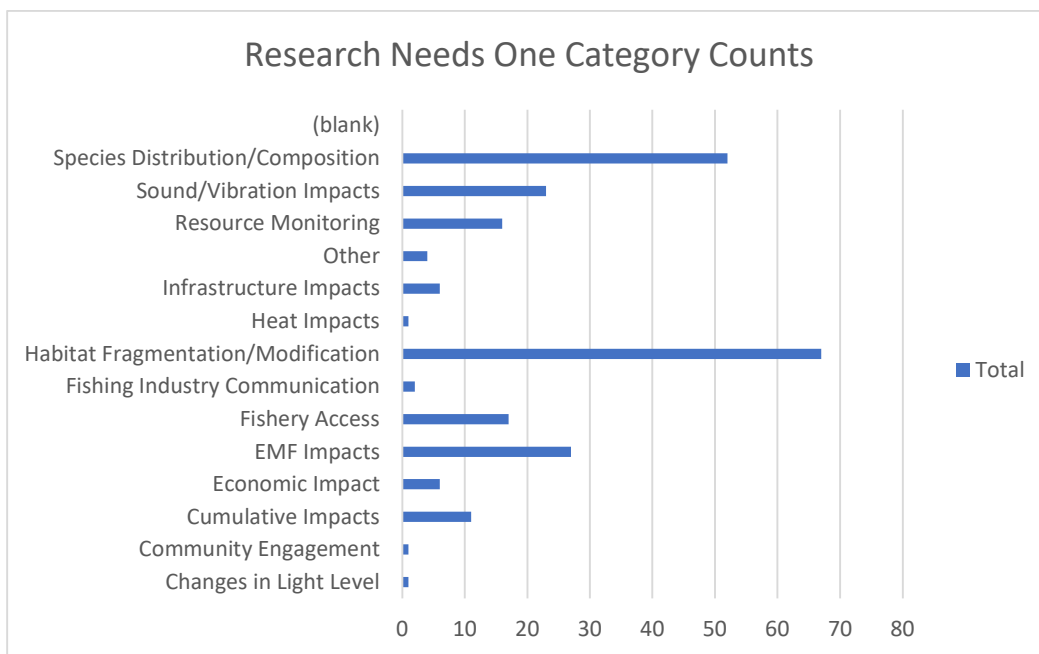


Figure 64 Fish Forward Database Research Needs 1

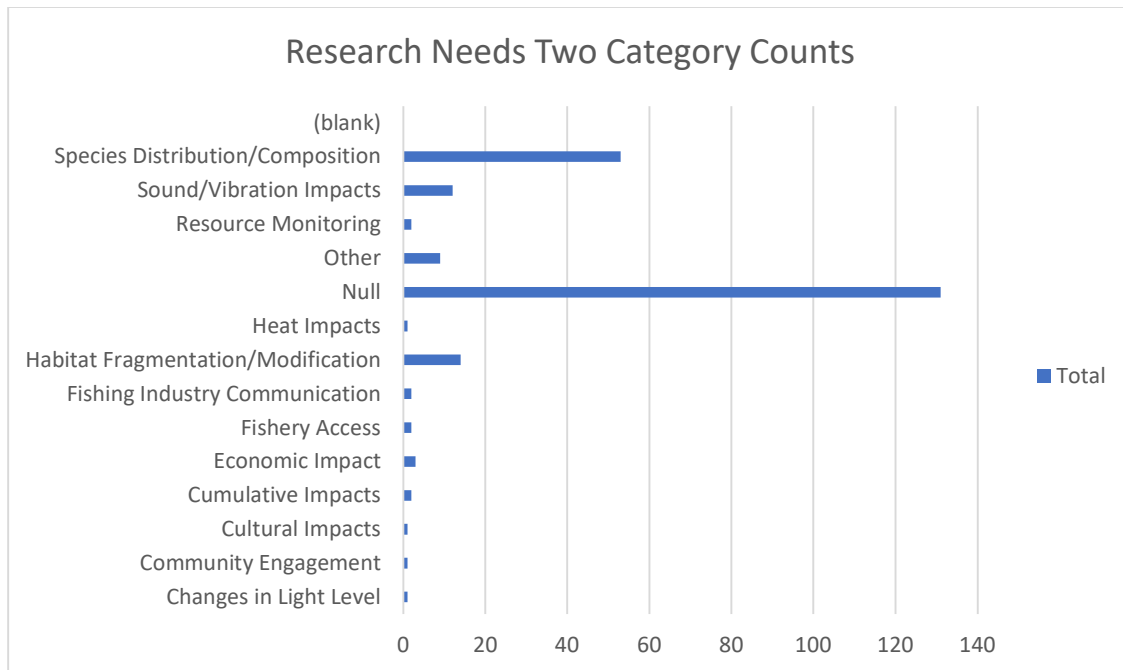


Figure 65 Fish Forward Database Research Needs 2

Finally, the RWSC has created a database tracking ongoing/past projects related to environmental impact. In addition to this database, the RWSC published an integrated science plan in 2023 (RWSC, 2024). This science plan was published to be a living document and uses many of the same recommendations that are published in the SEER database. In addition to the direct research recommendations, a significant portion of the science plan is dedicated to the importance of collecting, standardizing, and sharing data. While it may not be a specific research recommendation focused on a technology or a species, data standardization and availability are a key part of NIOWFs. This information will be needed to measure the success of different features and monitor the impacts of this new sector.

7.3.7 What should the goals for a nature inclusive wind farm be?

First, the goals for any net positive biodiversity increase will depend on the local ecology of a region. The Dutch report discussed earlier about the potential for flat oyster restoration in different potential OW sites is a good example of this opportunity (van Duren et al., 2022). Another example of a

location specific NID feature would be the ReCoral trial by Orsted at the Greater Changhua OW farm that looks to combine OW jacket foundations with coral restoration efforts (Orsted, 2023). In a panel discussion, experts stated that the United States Fish and Wildlife Service (USFWS) consults with BOEM early in the lease identification process using a no net loss policy for their mitigation hierarchy (Jedele et al., 2023). At this stage, the actual impact of a net positive framework being used in addition to the conventional no net loss policy can only be theorized.

This specific challenge was also discussed at the MOCEAN meeting. Participants discussed that the commonly used phrase “net-positive impact on biodiversity” is difficult to define because biodiversity can be a loaded term. This led to a discussion about what metrics would be useful to measure for biodiversity including: focusing on impacts to charismatic megafauna, focusing on species under the Endangered Species Act (ESA), focusing on a few key commercial species, and the potential for other techniques such as e-DNA to play a role. The discussion at MOCEAN was a preliminary exploration of the topic but it highlighted the need to create specific metrics to define biodiversity.

7.4 Conclusion

The NIOWF framework sees new OW development as a unique opportunity to be a cornerstone to a *New Blue Economy* centered on environmental stewardship, equitable economic development, and energy generation. Europe’s OW industry offers imperfect, but effective insights into a starting framework for building socially equitable and environmentally responsible OW wind farms. As the US OW industry grows, it can apply lessons from Europe and improve on NIOWFs by focusing on marine spatial planning, multi-use, and nature inclusive design. To build NIOWFs, the U.S. will need to set some additional groundwork and establish some additional partnerships, including the following:

- 1.) Paper studies identifying key barriers and opportunities for multi-use OW zones similar to the MUSES project in the EU.

- 2.) Baseline studies monitoring key species off the U.S. East Coast to establish the baselines needed to determine future impacts of OW farms.
- 3.) Outreach to key coastal communities involved in the seafood industry to identify techniques for coexistence including the potential for multi-use.
- 4.) Additional studies on key coastal communities to determine key concerns.
- 5.) Monitoring of wind farms that are already built and are currently under construction in order to measure environmental effects.
- 6.) Pilot projects inside of OW farms to test the viability of co-locating other economic activity (i.e. tourism, aquaculture, etc.).
- 7.) Development of metrics to define success.

Conclusions & Key Findings

The European OW started building some of the first generation monopiles as early as 2002. It was not until around 2016 with the MUSES project that Europe started to look at OW as a part of the larger blue economy and ocean ecology. The US should not have to wait over ten years to plan how OW farms will fit into our ocean environment and economy. The NIOWF framework expands the lens from an industry focused on only on power production into an industry that is a primary pillar of a *New Blue Economy* centred on environmental stewardship, equitable economic development, and efficient clean power generation. While NIOWFs are the vision, there is a lot of groundwork needed in the US to get there including:

- Paper studies that identify key barriers and opportunities for multi-use OW zones similar to the MUSES project in the EU. This article starts by identifying the lack of a wholistic MSP system for US federal waters, but more work is needed talking to stakeholders from coastal communities as well as other ocean users.

- As a part of this outreach to the seafood industry will be critical. The goal should be to identify techniques for coexistence including the potential for multi-use. Multi-use here refers to either the combination of offshore wind farms with restorative aquaculture or intentional adaptation strategies for fishing within offshore wind farms. Research from the UK has shown that merely opening the wind energy areas is not enough.
- More work is needed to understand the concerns of coastal communities.
- A review of research databases from critical US organizations confirms that more baseline studies monitoring key species off the U.S. East Coast are needed. This is more relevant to the mitigation hierarchy, but nature inclusive design is impossible to build without a solid foundation in the marine sciences.
- In addition to baseline testing there should be active monitoring of offshore wind farms that are being built and are currently operating in order to measure environmental effects. The beginning of offshore wind construction in the US creates an exciting opportunity to test different NID features such as scour protection or fish hotels.
- Metrics need to begin to be developed now in order to measure the success of different frameworks. Right now, even if the US wanted to financially support NIOWFs the metrics and goals are not in place to measure success.
 - Nature inclusive or net positive impact are generally quite vague terms. For example, if a wind turbine foundation forms an artificial reef and concentrates marine life in a location is that a success? Now is the time to have conversations with marine biologists, the seafood industry, coastal community members, Indigenous tribes, and other ocean stakeholders to visualize what success would be for a wind energy area.
- After the paper studies are completed, basic marine science is established, and goals/metrics are defined projects need to be tested at OW farms. Multi-use in particular is an exciting opportunity to test

the viability of co-locating other economic activity (i.e. tourism, aquaculture, etc.) within offshore wind farms. This could be a win-win for projects and communities in two ways.

- A key phrase that comes up when individuals are worried about the environmental impacts of offshore wind farms is “industrialization of the ocean.” If a positive shared vision for the role of OW energy areas in the ocean can be established, it could assuage these concerns. For example, in the Netherlands the efforts to establish seafood production in and around offshore wind farms allows them to set aside more of their ocean for marine conservation.
- Another way this can be a win-win is to help with economic concerns. Many coastal communities rely heavily on tourism and fishing two industry that often worry about the impact of offshore wind.
- The way OW works in the US and the way the US is broken up more generally does pose some additional challenges for planning and coordinating NIOWFs.
 - Unlike in Europe where the lease sales and procurement are typically handled by the federal government, in the US lease sales and permitting are controlled at the federal level while procurement is controlled at the state level. This can pose a challenge for coordination.
 - Each state can be incentivized to ask companies for “local content,” supply chain development, and marine research related to their own state projects. More coordination is needed between states when they procure OW.
 - The federal government has recently gotten more creative by adding bid credits to the leases for things like community benefits agreements, supply chain development, and fisheries management. However, on the east coast many of the lease areas were sold before the implementation of the multi-factor auctions so these credits do not affect projects being built right now.

- The US does not have the same laws and goals as the European Union requiring regional marine spatial planning. Some states have MSP, but offshore wind is not being developed in state waters. Instead BOEM in their lease identification process is essentially having to play the role of MSP coordination. There should be an effort to support MSP in the US to build a comprehensive vision and strategy for the ocean.

Primary Contributions of PhD Research

This work was inspired by a proposal that went to NSF for MOCEAN. The goal of that proposal was to build an organization that focused on three pillars energy production, environment stewardship, and economic development. Efforts in Europe have focused on combining offshore wind energy and environmental stewardship under the NID umbrella but economic development lens had not historically been well incorporated. This work adds in the economic development lens to NID under the new umbrella term nature inclusive offshore wind farms NIOWFs. This NIOWF framework was then applied to Europe and found that there were three main approaches policy (MSP), marine biology (NID), and economic development/commercialization (multi-use). In the NID framework these three fields are all interconnected and critical for NIOWFs. This same breakdown of MSP, NID, and NIOWFs was applied to the US to identify key stakeholders and organizations that would need to coordinate to apply the NIOWF framework to the US market. After sketching out the US market and comparing it to Europe key barriers to US NIOWFs were discussed in the last section. This positive vision for the ocean has not been clearly established and backed up by research work in Europe previously in the literature.

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Chapter 8 Conclusions

The complex interplay between corrosion and fatigue in offshore wind support structures has been examined, with a focus on the monopile foundations that dominate the OW industry. Through a systematic analysis of internal corrosion protection systems, corrosion-fatigue capacity testing, fatigue demand estimation, and nature-inclusive design approaches, this work has contributed to the understanding of how these degradation mechanisms affect the structural design, integrity, and longevity of offshore wind installations. The research has bridged gaps between laboratory testing, design standards, and field observations, providing insights that can inform more reliable and sustainable offshore wind infrastructure development which include nature-inclusive design.

This concluding chapter is divided into three main parts. The first part presents key points and findings from the review of the technical literature, comparative evaluation of requirements, examination of available data, and discussions with members of the design and research communities; this includes some analyses and ideas developed by the author. Next, a summary is provided of what the author considers to be the primary contributions of his PhD work. Finally, some concluding remarks and recommendations are made.

8.1 Key Points and Findings

This dissertation provided a fairly detailed description of a large array of requirements, an analysis of data and a state-of-the-art understanding of the author's assessment of critical uncertainties as well as suggested best practices. The next few pages provide a collection of the key points and findings from Chapters 2-7 to provide future researchers and the industry with a summary of key information and ideas to draw from and build upon.

Key Findings Chapter 2:

- The earliest generation of offshore wind monopiles built from 2002-2009 had significant shortcomings in their designs. While there are conference papers reporting observed problems and retrofitting efforts, the full story has not been compiled in one review. The two main problems were:
 - The grouted connection between the monopile and transition piece failed due to fatigue loading.
 - The designs assumed that the inside of monopiles were sealed such that the oxygen and dissolved oxygen would be fully consumed before any significant internal corrosion would develop. This faulty design assumption exposed unprotected steel surfaces to severe corrosion issues inside of monopiles. (Details in Chapter 3)
- The internal corrosion issue highlights the interdisciplinary nature of offshore wind monopile design. Corrosion and fatigue damage are two different mechanisms, but when they are combined into the chemical/mechanical process of corrosion-fatigue, the sum of the two is greater than each individual part. Corrosion-fatigue damage occurs in a complex feedback loop that is difficult to model. For example, when this historical issue with monopile design corrosion occurred and corrosion protection was applied, it created a problem from a corrosion-fatigue damage modeling standpoint.

Key Findings Chapter 3:

- There are a variety of viable options for internal corrosion protection systems used in industry. Limited information is available about their long-term performance to assess which is the most cost-effective option for different scenarios.
- The three main categories of internal corrosion protection are:

- Internal coating, unperforated, with no CP
- Internal coating, unperforated with zinc CP
- Internal coating, perforated, with ICCP (maybe aluminum as well)
- Perforations in the monopile are a popular choice of internal corrosion protection systems even though they are not well represented in the literature.
- For an aluminum anode system water replenishment is critical to avoid large drops in pH. A water replenishment rate of around 10% per day is commonly found in the literature.
- For an impressed current system, perforations are important to maintain the pH and to ventilate dangerous gases such as chlorine.
- The technology to monitor corrosion exists but has not been formally put into practice in a systematic way throughout the industry.
- There is an opportunity to incorporate the environmental impact of perforations into the design process of the monopile, potentially for ecosystem enhancement.
- In a young industry, there are wide gaps between what the industry knows, what is in the published literature, and what is in design guidance documents. Because of these disparities, the expertise of the corrosion protection designer is critical to the long-term performance of corrosion protection systems. This is a critical point to remember for stakeholders with oversight obligations such as regulators.
- Marine structure design is a highly interdisciplinary field. One small design decision, like perforations, can interact with the corrosion protection system, structural design, and the biological impacts of a structure.
- Information can become siloed within disciplines. This is particularly important as the industry moves into new markets and the technical workforce expands. To counter this risk, it is

important to survey the industry experts and ideally gather interdisciplinary teams to identify gaps in the available literature.

- A deeper understanding about the environmental effects of offshore wind monopiles will also be needed to support increased interest in combining wind energy areas with aquaculture across the larger blue economy. The impact of metal emissions from cathodic protection systems stands out as a particularly important research gap.

Key Findings Chapter 4:

- Recent corrosion-fatigue testing (SLIC) focused on compact tension specimen testing to determine the Paris Law coefficients for linear elastic fracture mechanics (LEFM). This testing updates relationships that were originally established in testing programs from the 1980s that identified key variables such as:
 - Testing Frequency – Corrosion is a time dependent process thus corrosion-fatigue crack growth rate is very sensitive to frequency.
 - Mean stress effect – This is represented by the loading ratio R In testing this is often discussed in the context of residual stress. In practice DNV-RP-c203 has an adjustment factor that reduces the stress cycle amplitudes in compression.
 - Temperature – Temperature is an interesting variable because it was not a focus of modern testing. One of the most popular testing programs, Scott & Thorpe, found that the crack growth rate doubled when temperature changed from 5 C to 20 C. This could have had a major impact on design of offshore wind farms in warmer waters such as off the coast of Virginia which is where the largest U.S. offshore wind farm is currently under construction. However, a review article from Jakubowski found the Scott & Thorpe result to be an outlier.

- Cathodic Protection – The best variable to measure the effectiveness of cathodic protection is the electropotential of the metal. When the metal is under normal cathodic protection conditions –850 mV the fatigue crack growth rate is around 2.5 times faster than in-air crack growth rates. Under free corrosion conditions, the rate is even faster, 3 times higher than the in-air crack growth rate. It is important to note that when steel is over protected above -1000 mV the crack growth rates get higher.
- Material Type – Most foundation components are made using typical low carbon steel such as S355. Testing has shown that high strength steels can be more susceptible to hydrogen embrittlement which makes them more difficult to use in a marine environment. Modern testing also shows that S355 steel that undergoes more advanced processing (TCMP) does not have a better corrosion-fatigue performance than regular normalized steel.
- SN testing is more expensive and difficult to run because it covers the entire fatigue life of the detail, including crack initiation. When testing in-air, it is possible to accelerate the tests by increasing the frequency to around 5 Hz but for corrosion-fatigue testing that is not possible. The limited amount of SN testing shows:
 - Looking to the past, the environmental reduction factors that represent the fatigue life reduction due to corrosion conditions are very scattered. The use of 3 for free corrosion and 2.5 for cathodic protection is reasonable based on the available data, but the results are not well clustered.
 - The thickness adjustment in the recommended practices is likely conservative based on the limited amount of testing available for thick specimens above 50 mm thick plate.
 - Recent work using a database of corrosion-fatigue testing found that there was not sufficient testing available to build an uncertainty model.

- Even if there was enough testing available constant amplitude it would not be relevant for the second half of the SN curve with the shallower slope $m = 5$. This has consequences for Chapter 5.
- While LEFM testing only accounts for the long crack growth phase of fatigue damage, it is often used to investigate the relative importance of different variables. For example, one review of SN testing from the 1980s corrected temperatures for one of the testing programs using LEFM behavior. The ERFs selected for the SN curves are also 3 for free corrosion and 2.5 for cathodic protection which is in part due to the SN data but also agrees with LEFM data.

Key Findings Chapter 5:

Note: All findings here are applicable only for the specific assumptions used in this analysis:

- The selected detail is a D-class butt-weld on a jacket leg.
- A modal expansion method was used to find strains because strain gauges were not available on the jacket leg. This means that the strains could not be verified via direct measurement.
- A basic extrapolation method was used that assumes the one-year monitoring period is representative of the lifespan of the structure.
- With these assumptions in mind the following items were identified:
- Even with a very conservative SCF estimate as high as 2, the estimated remaining life of the weld was over 100 years. This means that even with the most conservative DFF from DNV-ST-0126, $DFF = 3$, the weld still has significant remaining fatigue capacity.
- The second half of the SN curve with a slope of $m = 5$ above $1E7$ cycles consistently accounted for at least half of the measured damage across all cases.
- It was found that when Damage Equivalent Stresses were calculated using equations with a single slope that the damage associated with that DES was consistently higher than the damage

calculated using the bi-linear slope curve. This is because both halves of the SN curve account for a significant proportion of damage so using a single slope of $m = 5$ or $m = 3$ inevitably leads to one set of stress cycles overestimating the damage.

- Although the SCF has a significant impact on topline results such as the total damage measured and remaining fatigue life the impacts on relationships to fatigue demand are more subtle.
 - There was some sensitivity tied to the proportion of damage coming from each month of measurements. This sensitivity could be related to the relative importance of the stop condition.
 - There was a minor sensitivity to the proportion of damage coming from each wind speed bin. As the SCF increased, the relative importance of lower wind speeds in region 2 appeared to increase in importance by a very small amount.
 - It is likely that using a simplified fatigue damage such as the damage from nominal stresses at the tower base could still provide insight into fatigue demands.

Key Findings Chapter 6:

Rather than specific recommendations the key findings from chapter 6 are a generalized framework/guide for corrosion-fatigue analysis of weld details using SN curves, which consists of the following steps.

1. Obtain a stress time series either at a point of interest from either a strain gauge, modal expansion technique, or other techniques.
2. Apply a stress concentration factor (SCF) that is appropriate for the point of interest. If it is a butt weld with no significant thickness change an SCF of 1 is likely close enough. If there is a significant thickness change, the SCF may be somewhere between 1-1.5, but most likely around 1.2. If it is at a conical transition weld, the SCF is likely somewhere between 1.5-2 and 2 would be

a reasonable initial guess. More accurate SCFs could be calculated using the equations from DNV-RP-c203 or from a detailed FEA analysis.

3. Run the rainflow count.
4. Calculate damage equivalent stresses (DES) using a slope of $m = 5$ and the equation from Sadeghi et al. As shown in chapter 5 the DES will likely overestimate the fatigue damage to some extent, but it is a very helpful metric to compare across different elevations of a monopile to find key areas of interest.
5. Select an SN curve for the analysis. A circumferential butt weld on a monopile is typically a D-class weld (per DNV documents). If the weld is ground, it can be taken as a C1 class weld. If the weld is in the submerged zone or lower, using the cathodic protection curve for the full life of the structure is reasonable/close enough. If the weld is in the splash zone, use the in-air curve for 15-20 years and then extrapolate using the free corrosion curve for the remaining life.
6. Apply the bi-linear SN curve to the rainflow count of the stress time series. The DES can be directly converted to a damage index but based on chapter 5 this will be a conservative estimate of the projected fatigue damage.
 - a. Note: The rainflow count will also provide the user with mean stress. Following DNV-RP-C203 stress cycles that occur with a mean stress that is in compression can be reduced in magnitude. In this work none of the welds have been close to failing due to fatigue so this adjustment has been ignored making the estimates more conservative.

Key Findings Chapter 7:

The European OW started building some of the first generation monopiles as early as 2002. It was not until around 2016 with the MUSES project that Europe started to look at OW as a part of the larger blue economy and ocean ecology. The US should not have to wait over ten years to plan how OW farms will fit into our ocean environment and economy. The NIOWF framework expands the lens from an

industry focused on only on power production into an industry that is a primary pillar of a *New Blue Economy* centred on environmental stewardship, equitable economic development, and efficient clean power generation. While NIOWFs are the vision, there is much groundwork needed in the US to get there including:

- Paper studies that identify key barriers and opportunities for multi-use OW zones similar to the MUSES project in the EU. This article starts by identifying the lack of a holistic MSP system for US federal waters, but more work is needed talking to stakeholders from coastal communities as well as other ocean users.
 - As a part of this, outreach to the seafood industry will be critical. The goal should be to identify techniques for coexistence including the potential for multi-use. Multi-use here refers to either the combination of offshore wind farms with restorative aquaculture or intentional adaptation strategies for fishing within offshore wind farms. Research from the UK has shown that merely opening the wind energy areas is not enough.
 - More work is needed to understand the concerns of coastal communities.
- A review of research databases from critical US organizations confirms that more baseline studies monitoring key species off of the U.S. East Coast are needed. This is more relevant to the mitigation hierarchy, but nature inclusive design is impossible to achieve without a solid foundation of baseline and marine research.
- In addition to baseline testing, there should be active monitoring of offshore wind farms that are being built and are currently operating in order to measure environmental effects. The beginning of offshore wind construction in the US creates an exciting opportunity to test different NID features such as scour protection or fish hotels.

- Metrics need to begin to be developed now in order to measure the success of different frameworks. Right now, even if the US wanted to financially support NIOWFs, the metrics and goals are not in place to measure success.
 - Nature inclusive or net positive impact are generally quite vague terms. For example, would it be considered a success if a wind turbine foundation forms an artificial reef and concentrates marine life in a specific location? Now is the time to have conversations with marine biologists, the seafood industry, coastal community members, Indigenous tribes, and other ocean stakeholders to visualize what success would be for a wind energy area.
- After the paper studies are completed, basic marine science is established, and goals/metrics defined, projects need to be tested at OW farms. Multi-use, in particular, is an exciting opportunity to test the viability of co-locating other economic activity (i.e. tourism, aquaculture, etc.) within offshore wind farms. This could be a win-win for projects and communities in two ways.
 - A key phrase that comes up when individuals are worried about the environmental impacts of offshore wind farms is “industrialization of the ocean.” If a positive shared vision for the role of OW energy areas in the ocean can be established, it could assuage these concerns. For example, in the Netherlands the efforts to establish seafood production in and around offshore wind farms allows them to set aside more of their ocean for marine conservation.
 - Another way this can be a win-win is to help with economic concerns. Many coastal communities rely heavily on tourism and fishing, two industries that often worry about the impact of offshore wind.

- The way OW works in the US, and the way the US is broken up more generally, does pose some additional challenges for planning and coordinating NIOWFs.
 - Unlike in Europe where the lease sales and procurement are typically handled by the federal government, in the US lease sales and permitting are controlled at the federal level while procurement is controlled at the state level. This can pose a challenge for coordination.
 - Each state can be incentivized to ask companies for “local content,” supply chain development, and marine research related to their own state projects. More coordination is needed among states when they procure OW.
 - The federal government has recently become more creative by adding bid credits to the leases for things like community benefits agreements, supply chain development, and fisheries management. However, on the east coast, many of the lease areas were sold before the implementation of the multi-factor auctions so these credits do not affect projects being built right now.
 - The US does not have the same laws and goals as the European Union requiring regional marine spatial planning. Some states have MSP, but offshore wind is not being developed in state waters. Instead BOEM in their lease identification process is essentially having to play the role of MSP coordination. There should be an effort to support MSP in the US to build a comprehensive vision and strategy for the ocean.

8.2 Primary PhD Contributions

The contributions of the author were distributed throughout the dissertation, and a chapter-by-chapter summary of these are given below.

Chapter 3

Chapter 3 provides history of corrosion issues inside of monopiles had not been previously compiled beyond conference papers on individual topics. Requirements from design documents and industry insights were analysed to understand the interaction of corrosion protection methods, fatigue design, and holistic foundation design. Based on this, new insights were made into how to design suitably robust internal corrosion protection systems.

Chapter 4

Chapter 4 presents a detailed analysis of corrosion-fatigue capacity testing, examining how environmental conditions interact with loading variables to affect fatigue performance. This examined data from linear elastic fracture mechanics testing as well as SN curve testing. Based on this, the limitations in available data and the impact of these limitations on damage and design life were assessed and presented.

Chapter 5

Chapter 5 connects fatigue demands from an offshore wind structure with the SN curves discussed in Chapter 4. While there is significant SHM research about the fatigue demands on offshore wind turbine support structures, much of this work uses the damage equivalent load/stress metric. This simplified metric only accounts for the assumed slope of the SN curve and does not capture the true behaviour of fatigue testing that we see in the SN data. The fatigue demand data from an offshore wind jacket is used to answer critical questions, such as:

- What are the consequences of using the equivalent stress simplification?
- What section of the SN curve is driving the damage and what testing should be done to fill the gap?
- How sensitive is the relationship between measured fatigue damage and environmental conditions to capacity assumptions such as the SCF?

Chapter 6

Chapter 6 provides a generalized framework/guide for fatigue analysis. The gaps between how fatigue demands are usually calculated by modelers and digital twin builders versus how fatigue testing is done, and SN curves are calculated, was examined. The results of this were used to suggest the need for new testing combining pre-corroded specimens and variable amplitude loading. No work on this important matter appears to be in the technical literature, or under investigation by the leading research groups in the world on such matters.

Chapter 7

The responsible design of offshore wind support structures is not only that they provide the needed level of structural reliability, but also that these structures strengthen or do no significant harm to the marine ecosystem. Recent efforts in Europe have focused on combining offshore wind energy and environmental stewardship under a Nature-Inclusive Design (NID) umbrella, but the economic development lens has not historically been well incorporated. The author's work contributes an economic development lens to nature inclusive offshore wind farms NIOWFs. The proposed NIOWF framework was then applied to Europe and found that there were three main approaches: policy (MSP), marine biology (NID), and economic development/commercialization (multi-use). In the NID framework these three fields are all interconnected and critical for NIOWFs. This same breakdown of MSP, NID, and NIOWFs was applied to the US to identify key stakeholders and organizations that would need to coordinate to apply the NIOWF framework to the US market. After sketching out the US market and comparing it to Europe key barriers to US NIOWFs were discussed in the last section. Any positive vision for the ocean in the US OW market has yet to be clearly stated and backed up by European research.

8.3 Concluding Remarks & Recommendations

This work was all about bridging connections and finding the gaps between different information silos in the offshore wind space. Some of these gaps were within specific disciplines such as fatigue assessment. Other gaps were between engineering disciplines such as corrosion protection engineers and structural engineers. Finally, gaps between our engineered structures and the surrounding environment and society were addressed through the lens of NIOWFs. A summary of the key findings covering these information gaps alongside recommendations for future research and design practice have been summarized and presented below.

When discussing fatigue, this work has been summarized as the “capacity side” of the fatigue assessment while the modeling and monitoring work make up the “demand side”. This mental model of fatigue analysis is true in part, but one of the key thrusts of this work has been to show that they are intrinsically linked. For example, the damage equivalent load (DEL) metric is popular in “demand side” research and analysis for a good reason; it provides a stable metric to compare fatigue demands because it is only dependent on the slope of the SN curve and no other material properties. However, as shown in chapters 4 and 5 this strength of DELs can also be a weakness. This is best exemplified in two novel findings found at the intersection of demand and capacity:

1. The DEL framework overestimates the measured fatigue damage compared to the bi-linear nature of the SN curves used in design.
 - a. The consequence of this finding is that the preferred metric used to compare fatigue damages to one another is likely conservative. If these DELs are then being directly converted to damages without reanalysis using a bi-linear curve, this could be overestimating the actual damage at a detail.
2. The second half of the SN curve with the slope of $m = 5$ accounted for over 50% of the total cumulative damage measured in the weld examined for this work. Damages extrapolated from DELs

calculated using the $m = 5$ slope were also much closer to the damage calculated using the bi-linear SN curve than the damage extrapolated from DELs calculated using the $m = 3$ slope.

- a. The consequence of this finding is that a testing program is needed to investigate the effects of corrosion-fatigue conditions on specimens with variable amplitude testing. More research should focus on the $m = 5$ section of the curve and the Haibach adjustment should be investigated more deeply.

The interdisciplinary nature of this work also extends beyond bridging fatigue demand and fatigue capacity. Analysis of corrosion protection practices in the offshore wind industry shows that the simplified model of corrosion-fatigue damage with three environments: in-air, cathodic protection, and free corrosion is not entirely accurate to the actual experience of offshore wind platforms. Corrosion can occur on an offshore wind foundation for a variety of reasons including lag time between monopile installation and cathodic protection system activation, coating damages, microbiologically influenced corrosion, or failures in the cathodic protection system from some combination of reliability issues or design flaws. Recommendation: More corrosion-fatigue testing focused on crack initiation is needed to fill this gap and allow for fatigue analysis to be done when there is a period of temporary corrosion.

The NIOWF framework expanded naturally out of the preliminary investigations into the impacts water replenishment holes in a monopile could have on the environment. It also tied nicely into other related work that was analyzed about the risk of metal emissions from cathodic protection systems. These two examples inspired a framework the NIOWF to see how engineering design decisions have downstream effects on the environment and society. For example, one of the common arguments made when metal emissions are described as a concern is that they end up being diluted in the large ocean. However, if NID features are being added to have a net positive impact on biodiversity, does that affect the risk calculation? This example then ties into the previous two because if an impressed current system is considered to avoid metal emissions what does that do to the overall design life of the foundation.

Ultimately offshore wind foundations should be considered as long-term durable infrastructure, especially if they are to be used as artificial reefs in the context of net positive impacts to biodiversity. The most sustainable OW foundation would be one that does not need to be replaced every 25 years. With this vision in mind, the following key recommendations are made:

1. More data on the reliability of offshore wind cathodic protection systems should be collected.

While there is a rich history of corrosion on the early monopiles due to issues with the initial designs, there is much less information about the reliability and performance of modern systems. The OW industry already has methods in place for anonymizing information related to SCADA and SHM data. As corrosion monitoring grows in popularity, there should be efforts to share it for the purposes of benchmarking and the overall health of the industry.

2. More corrosion-fatigue testing is needed, particularly SN testing. Although it is more expensive than LEFM testing, SN testing is the only way to study the combined effects of variable amplitude loading and pre-corrosion on welds. Without additional testing it will not be possible to update corrosion-fatigue damage models. As SHM techniques improve and the industry gets better at digital twinning it is a waste to plug in such hard-won information on fatigue demands into simplistic fatigue models.

3. There needs to be a greater discussion on the vision for OW in the U.S. and how it fits into the larger *New Blue Economy* in a sustainable fashion. It is also critical that engineering professionals are involved in this conversation because of the complex interactions between the built systems and the natural environment.