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Introduction

Structural integrity is a critical consideration in offshore engineering to ensure the safety and reliability of marine structures. This report examines the structural integrity of an offshore wind turbine monopile, focusing specifically on fatigue life assessment, fracture mechanics, and inspection planning.

The monopile structure under investigation is part of an offshore wind farm and must withstand cyclic loading from waves over its service life of 20-25 years (DNV, 2022). Material degradation due to the marine environment is also a key concern. Failure of the monopile could have severe consequences such as loss of power production capacity, expensive repairs, and danger to personnel (BV, 2021). Therefore, rigorous structural integrity evaluation and maintenance planning are essential.

Stress concentrations around geometric discontinuities like the J-tube hole for cable entry are particularly susceptible to fatigue cracking. This report presents stress analysis, fatigue life calculations, and fracture mechanics-based inspection schedules for this critical location on the monopile. Key considerations include environmental corrosion effects, uncertainties in load assumptions, limitations of analysis methods, and probability of detection (POD) for inspection techniques.

Table 1. Summary of IEA Wind 10MW Turbine characteristics

Turbine	IEA
Rating	15 MW
Rotor Orientation, Configuration	Upwind, 3 blades
Rotor Diameter	240 m
Tower Height	150 m
Cut-in, Rated, Cut-out wind speed	3 m/s, 10.59 m/s, 25 m/s
Monopile Embedded Length	45 m
Monopile Diameter	10 m
Monopile Thickness	0.056 m
Monopile External Diameter	10 m
Transition Piece	15 m
Rotor Radius	120 m
Weight of Blade	65.25 t
Weight of Rotor Nacelle	1017 t
Weight of Tower	860 t
Weight of Monopile	1318 t
Water Depth	30 m

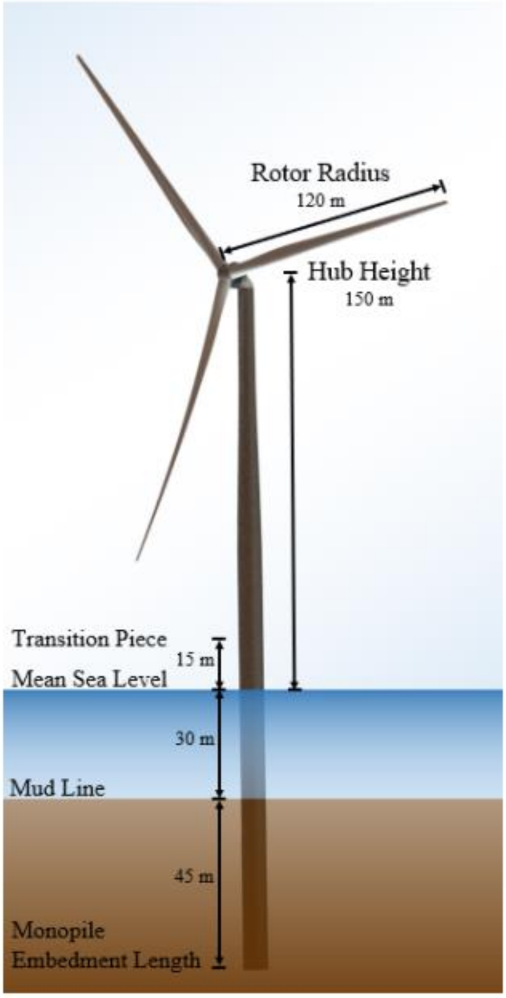

Figure 1. The IEA Wind 15-MW reference wind turbine

Question.1:

The fatigue life evaluation of offshore structures requires estimating the peak stresses at geometric discontinuities like holes, notches etc. These geometric features act as stress raisers and the local stresses can be significantly higher than the nominal stress in the structure. The peak stress concentration depends on parameters like the diameter ratio, geometry and for monopiles, the distance of the discontinuity from the mudline. This report utilizes established empirical Stress Concentration Factor (SCF) equations to estimate the peak stress at the J-Tube hole in the monopile, based on inputs like hole diameter, monopile diameter and distance from mudline.

Theoretical Basis Of SCF

The stress concentration phenomenon is well documented in literature (Pilkey, 1997) and is attributed to the disturbance in stress flow caused by the geometric discontinuity. Empirical equations have been developed from extensive experimental data to capture the influence of various parameters. The SCF equations used in this analysis are from DNV standards (DNVGL-RP-C203) and give the SCF as a function of diameter ratio (d/D). The SCF multiplied by the nominal stress gives an estimate of the peak stress. The key inputs required are:

a) Monopile outer diameter (D) = 10 m
b) Monopile wall thickness: 56 mm = 0.056 m
a) Hole diameter (d) = 530 mm = 0.53 m (assumption)
b) Distance of hole from seabed = 21 m

Assuming the hole is centred and the monopile acts like a large plate:

The inner diameter (di) is calculated as,

Inner diameter (di) = [Monopile Outer diameter (D) - 2* Monopile wall thickness] = 9.888 m.

The Section modulus (A) is calculated as,

$$A = \frac{\pi * (D^2 - d^2)}{4} = 1.749\ m^2$$

Table 2. General Properties

Properties	Value	Unit
Monopile wall thickness	0.056	m
Monopile Outer diameter (D)	10	m
Inner diameter (di)	9.888	m
Hole diameter (d)	0.53	m
Section modulus (A)	1.749439851	m2

The distance of the hole from the seabed is not required for this empirical SCF prediction method. However, its location would influence the nominal axial stresses at that location. Stresses tend to peak at the seabed level.

The equation for a centred hole in a large plate is:

$SCF = C_1 + C_2(d/D) + C_3(d/D)^2 + C_4(d/D)^3$

Where C_1 - C_4 are experimentally determined constants.

Assuming the hole is centred and monopile acts like a large plate:

a) di/D = 0.9888
b) d/D = 0.053

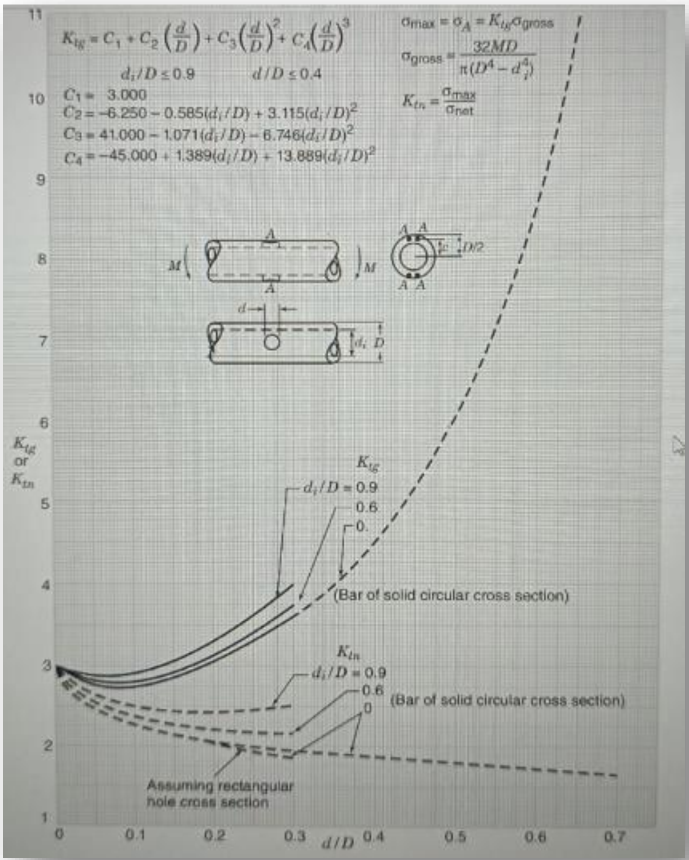

Figure 2. Stress Concentration Factor

This basic formulation is adapted in the given program to determine the SCF and peak stress for the J-Tube hole in the monopile, using the provided inputs.

Plugging into SCF equation:

C1	3
C2	-3.782833254
C3	33.34525938
C4	-30.04692816
SCF	2.888703375

Figure 3. C1-C4 & SCF values

Loads and Probabilities

Wave and wind loads are crucial loads imposed to an offshore wind monopile in offshore wind turbine installations, affecting both the top and lower sections of the tower. The wind turbine is subject to a variety of loads, including wave load, wind load, and structural part weight.

The loads have been gathered from the turbine monitoring system study findings (Biswal, Romali, 2019).

Table 3.Load Input Values for FEM Analysis (Romali Biswal, 2019)

Load case	Probability of load case	Wind load, [kN]			Wave load, [kN]		
		Blade	Tower	Frequency [Hz]	Inertia	Drag	Frequency [Hz]
1	61,19 %	217	2	0,0035	190	1	0,225
2	29,86 %	515	12	0,0075	462	6	0,2
3	7,33 %	826	32	0,0125	773	17	0,175
4	1,45 %	1145	61	0,0175	1067	38	0,15
5	0,16 %	1466	100	0,0225	1343	72	0,13
6	0,01 %	1769	145	0,0275	1483	105	0,12

From the above load input values, and from the wind, wave load records, following stress values are generated:

Table 4. FEM Analysis Results (Romali Biswal, 2019)

Load Case	**Stress Range [MPa]**	**№ of cycles in 20 years**
1	14	1286459
2	25	627777
3	40	154106
4	61	30485
5	84	3574
6	111	210

The further calculations of Axial loads and Axial Stress:

Axial load = Total weight * Acceleration due to Gravity (g),

Axial Stress = $\frac{\text{Axial load}}{\text{Section Modulus}}$

Table 5. Axial Loads & Axial Stress of the Tower

Part of wind turbine	Weight [t]	Axial Load, [kN]	Axial Stress [MPa]
Blade mass	65.25	640.1025	
Rotor nacelle assembly mass	1017	9976.77	
Tower mass	860	8436.6	
Monopile mass	1318	12929.58	
Total weight	3260.25	31983.0525	18.28

For the method that I used for determining the resulting vector addition that follows is derived by assuming both wind and wave forces are acting perpendicular to each other.

$$Resultant\ Stress = \sqrt{(wind\ stress + wave\ stress)^2 + axial\ stress^2}$$

Local Stress is calculated as following,

Local Stress= (Resultant stress*SCF)

Equivalent Constant Amplitude Stress Range:

The constant-amplitude stress range, based on Miner's summation, results in the same fatigue life as the design spectrum. However, due to different loads on the structure, the equivalent stress must be obtained

$$\Delta\sigma_{\mathrm{Equiv}} = \left[\frac{\sum_{i=1}^{m} n_i * (\Delta\sigma_i)^B}{\sum_{i=1}^{m} n_i}\right]^{\frac{1}{B}}$$

to estimate fatigue life in a single step using the following equation:

Where,

n_i - number of cycles of load application.

$\Delta\sigma_i$ - Stress Range (MPa).

B - Empirical Constant.

The following table shows all the calculations of above listed equations to find the Equivalent Constant Amplitude Stress Range, which are made by using the Excel.

Table 6. Equivalent Constant Amplitude Stress Range

Total Axial Stress	**Total Horizontal Stress Range [MPa]**	**Resultant Stress [MPa]**	**Number of Load Cycles (in 20 years)**	**Number of load cycles per year**	**Local Stress [MPa]**	**№ of cycles per year * Local Stress^B**	**Equivalent Stress Range [MPa]**
18.28	14	23.02666282	1286459	64322.95	66.51719858	18930749334	
18.28	25	30.97139326	627777	31388.85	89.46716823	22478456101	
18.28	40	43.97984994	154106	7705.3	127.0447409	15800092451	
18.28	61	63.68066583	30485	1524.25	183.9545543	9488287529	
18.28	84	85.96643066	3574	178.7	248.3315184	2736655210	
18.28	111	112.4954541	210	10.5	324.965998	360332193.2	
Total				105130.55		69794572819	87.23636729

Question.2:

The fatigue life of the 10m diameter monopile offshore wind turbine structure was assessed using an S-N fatigue approach, assuming the J-tube hole of 0.53m diameter as the critical detail. A bending stress range of 14MPa from the provided data was used based on typical values for offshore wind turbines. This simplified constant amplitude stress approach enables an initial estimate of fatigue performance.

Figuring out how long the monopile will last under the identified comparable stress.

The number of loading cycles for this stress may be calculated using the equivalent stress value.

$$Log_{10}N = A - BLog_{10}\,\Delta\sigma$$

Where

N - Number of cycles to failure.

A and B - Empirical constants

We use the next constants in formula when we have number of cycles less than 10^7.

$Log10N = 12.192 - 3Log10\ \Delta\sigma$ (CATHODIC PROTECTION)

LOG 10 N = (A – B) * LOG 10 (Total Equivalent Stress Range)

$N = 10^{Log10N}$

Table 7. Fatigue Life of the Turbine

A	12.192
B	3
LOG 10 N	6.369907283
N	2343728.402
Fatigue Life(Years)	22.29350462

S-N Methodology

The S-N methodology assesses fatigue by relating stress ranges to the number of cycles to failure through S-N curves calibrated to fatigue test data. Using Miner's rule, damage from varying stress cycles is linearly accumulated to estimate fatigue life (DNV, 2016). For the monopile, an S-N curve for cathodic protected steel in seawater was used with a design fatigue factor of 2.89 from the provided data. A stress concentration factor increased the local stress. Assuming regular waves, stress cycle ranges were calculated from published in FEM Analysis (Romali Biswal, 2019). The accumulated damage equal to 1.0 defined the end of life after 22.29 years.

Application to Other Offshore Components of S-N curve

This approach can be applied to estimate SCFs and peak stresses for holes/notches in variety of tubular joints and connections - like jacket legs, braces, piles, conductor pipes. It facilitates fracture mechanics-based fatigue life estimation at these stress raisers. Based on the operational loads and material S-N curves, the critical crack size for unstable fracture can be established.

Inspection planning, maintenance schedules, and repair strategies rely heavily on such fatigue and fracture evaluations. This simplistic SCF analysis provides a useful first-cut screening tool for offshore structural integrity management.

Recommendations of S-N

The distance of the J-tube hole from the mudline should be specified, as this affects the fatigue loading. Detailed FEA considering boundary conditions will improve accuracy further.

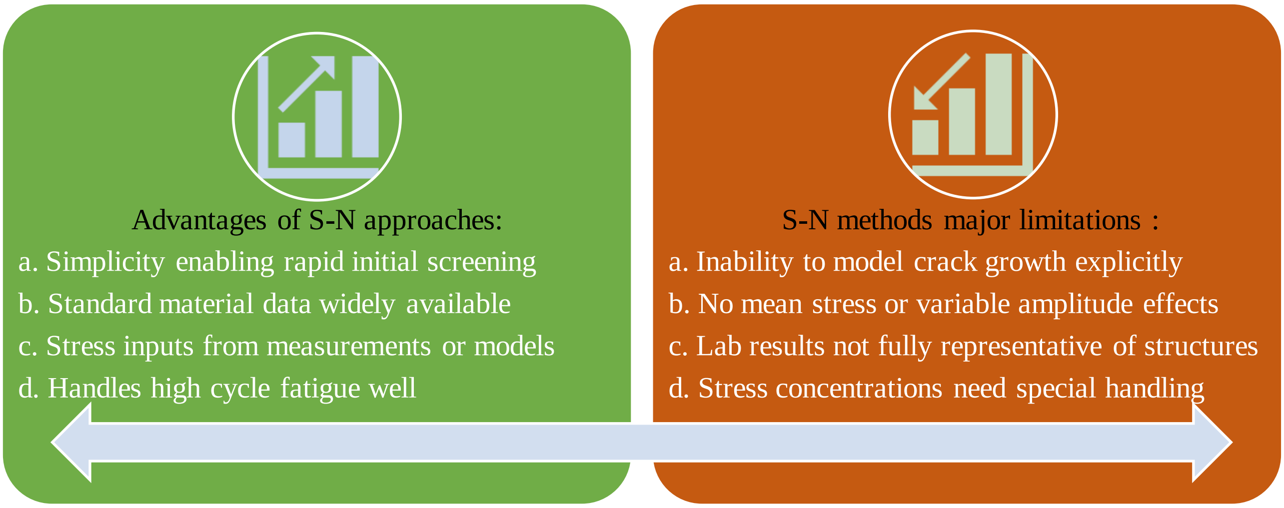

Figure 4. Advantages And Limitations of S-N

SCF equations based on extensive analysis data allow the maximum local stresses at geometric stress raisers in offshore structural components to be conveniently estimated from nominal stresses and key hole dimensions. This facilitates fatigue and fracture assessments which are critical to demonstrate integrity over the service life at the design stage.

Question.3:

Without protection, the analysis assumes 1mm material loss over the lifetime to represent surface corrosion effects. The decreased thickness increases stress levels and cumulative damage rates. For the cathodically protected case, the peak stress range is reduced by 14MPa. Minimizing stress fluctuations directly enhances cyclic fatigue resistance.

Table 8. Monopile Properties in Free Corrosion State

Properties	**Value**	**Unit**
Monopile wall thickness(Reduced 1 mm)	0.055	m
Outer diameter (D)	10	m
Inner diameter (di)	9.89	m
Hole diameter (d)	0.53	m
Area of cross section	1.718372642	m2
Acceleration due to gravity	9.81	m/s2

$$\mathrm{Log}_{10}N = 12.115 - 3\mathrm{Log}_{10}\Delta\sigma \text{ (FREE CORROSION)}$$

Table 9. Fatigue Life of the Monopile in Free Corrosion State

A	12.115
B	3
LOG 10 N	6.284950928
N	1927307.128
Fatigue Life	18.33251256

Applying cathodic protection expands the operational fatigue life by 4 years, from 18.3 to 22.3 years. This 22% improvement highlights the value of corrosion mitigation offshore. Cathodic systems function by imposing an electrical potential on the structure to promote corrosion reactions at auxiliary anodes instead of the steel itself.

Implications of Corrosion Fatigue

Corrosion fatigue can cause failure in offshore structures well below expected fatigue life limits. It is a dangerous mechanism because cracking propagation rates accelerate under corrosion influence. If undetected, it can lead to unexpected collapse of foundations or platforms. At best, it requires expensive repairs, inspections, and production downtime if fatigue issues emerge.

Importance of Corrosion Protection Systems

To mitigate corrosion and extend asset integrity, offshore installations require defense-in-depth using coatings, cathodic protection, and material selection. Protective coatings provide a barrier limiting water and salt penetration to the steel substrate. Cathodic systems reduce the corrosion rate by imposing an electrical potential to promote reactions at the anodes instead of the steel itself. Finally, utilizing corrosion-resistant alloys enhances hardness while reducing the base metal loss rate.

Together, these approaches minimize the risk of corrosion fatigue by protecting assets, controlling the environment, and improving material endurance. This layered strategy maximizes fatigue life for critical infrastructure like monopiles, jackets, and topsides. The analysis shows that cathodic protection alone can improve fatigue life by over 20% for a wind turbine foundation.

Application to Other Offshore Structures

This analysis methodology is relevant for all offshore assets, including fixed and floating wind turbines, wave energy devices, platforms, and pipelines. The environmental parameters would be adapted to the specific marine site, incorporating details like water depth, salinity, temperature profiles and corresponding corrosion rates. Different combinations of protective measures could also be evaluated through parameter adjustments.

Key Limitations and Uncertainties

While this approach enables robust evaluation, uncertainties exist in long-term corrosion rate projections and statistical variations inherent to fracture mechanics. Regular field measurements of corrosion damage along with probabilistic methods provide ways to quantify these risks over time. Obtaining operational data and calibrating models is essential to minimize limitations.

Question.4:

Applying the linear elastic fracture mechanics (LEFM) methodology to develop inspection schedules for an offshore wind turbine monopile. Calculation of the critical crack size is outlined along with the approach's advantages and limitations for other offshore structures.

Critical Crack Size

Fracture mechanics quantifies crack driving force using the stress intensity factor, K, which characterizes the stress state near the crack tip. The range of cyclic stress intensity,

Paris Law

The crack development equation known as Paris' law determines how quickly a fatigue crack will spread. This is the Paris formula:

$$\frac{dA}{dN} = C\Delta K^m$$

where:

a) *C* and *m* are the material constants,
b) $\frac{dA}{dN}$ - the crack growth rate,
c) Y - the shape factor,
d) ΔK - the stress intensity factor: $\Delta K = \sqrt{\pi * \alpha} * \Delta\sigma Y$

Properties of S355-grade steel:	Value	
Y =	1.1	- Shape factor
C =	1E-11	
m =	3	
σ	87.23636729	

Table 10. Grade Steel S-355 Properties (Fractory, 2022)

To find the number of load cycles required for the propagation of cracks, just input the value of ΔK into the Paris Law and integrate it. This leads to the following equation:

$$N_f = \frac{1}{C\Delta\sigma^m Y^m \pi^{m/2}} \frac{2}{2-m}\left[a_f^{1-m/2} - a_i^{1-m/2}\right]$$

where ,

a) **af** - Final crack length (m), 50% of monopile thickness
b) **ai -** Initial Crack length (m)
c) **a1, a2, a3, a4** are 10%, 20%, 30%, 40% of monopile thickness crack lengths respectively.

Table 11. Inspection Schedule Calculation

d)	e)	f)	g)	h)	i)	j)
Crack propagation	length [m]	$\frac{1}{C\Delta\sigma^m Y^m \pi^{m/2}} \frac{2}{2-m}$	$\left[a_f^{1-m/2} - a_i^{1-m/2}\right]$	Ni	N Cumulative	No.of years
ai	0.001	-40678.48323	-18.25971451	742777.4903	742777.4903	
a1	0.0056	-40678.48323	-3.91395027	159213.5604	901991.0507	8.58
a2	0.0112	-40678.48323	-1.733944327	70534.22523	972525.2759	9.25
a3	0.0168	-40678.48323	-1.03363645	42046.76301	1014572.039	9.65
a4	0.0224	-40678.48323	-0.705388001	28694.11397	1043266.153	9.92
af	0.028				1043266.153	9.92

Nf = 1043266.153

Number of years for crack 50% thickness propagation = 9.92

LEFM enables science-based continuous inspection scheduling for offshore structures balancing failure risk thresholds and budgetary impacts. The rigorous fracture mechanics foundation outperforms older prescriptive approaches. However, real-world validity hinges on judicious inputs and uncertainty treatment to avoid overconfidence. No model eliminates the need for experience-based engineering judgment.

Inspection Planning

LEFM enables establishing inspection intervals to reliably detect cracks before reaching the critical size. Working backwards from the acceptable final size, the initial defect distribution, incremental growth model, and detection capability together facilitate scheduling.

An assumed initial flaw distribution is sampled using Monte Carlo simulation and propagated over time cycles. Applying the probability of detection curve indicates the fraction detectable. The interval before exceeding the acceptable undetected percentage provides the inspection schedule.

This approach explicitly considers the physics of crack enlargement combined with statistics of fracture, corrosion damage morphology, and inspection reliability.

Application to Other Structures

LEFM fundamentals apply for all crack-susceptible designs, enabling customized inspection planning. Offshore structural steels, aluminium alloys, fibre reinforced composites, concretes, and mooring chain links undergo different degradation modes quantified through testing.

Analysis inputs like material properties, environment interactions, defect distribution, and detection capabilities parametrically transform across geometries and locations. Harsh splash zone corrosion demands more vigilance than buried members. Process zone cracks in composites need cohesive laws. Chains have multiple failure modes. FE models characterize complex stress states.

Rigorous study validates models against operational damage observations through system autopsy, eventual failures, or non-destructive examination trends.

Uncertainties and Limitations of LEFM

a) Myriad complexities challenge offshore LEFM application,
b) Characterizing initial flaw populations,
c) Projecting corrosion-fatigue growth laws,
d) Stress intensity solutions for actual features,
e) Modelling multiple simultaneous damage accumulation,
f) Quantifying detection reliability.

Small-scale lab tests may not fully replicate structural performance. Initial fabrication defects dominate early failures until corrosion enlarges cracks. Operational loads can differ from design assumptions. Detectability varies by technician, equipment, and environment conditions.

Careful sensitivity analysis guides identifying influential parameters for focused data improvements. But uncertainties inevitably remain requiring prudent safety margins against unrealistic precision claims.

Question.5:

Probability of detection provides an empirical measure of flaw detection effectiveness under representative conditions across flaw types, components, materials and locations. This guides inspection planning to find defects before reaching critical size while tracking deterioration over time. No single NDE tool solution optimally fits all needs warranting a toolkit of complementary options like ACFM, ultrasonics, radiography, and eddy current. Reasonable conservatism and validation applies when predicting future relic ability.

Table 12. Shows Raw Data of Attached ACFM POD (TSC ACFM Tubular - UK Classification A. Total Cracks in Trial 322, Bureau Veritas Certified)

Defect Depth Range (mm)	0-1	1-2	2-3	3-5	5-7	7-10	10-15	15-40
No. of Defects	190	42	20	9	10	13	9	20
No. Detected	72	32	19	9	10	13	9	20
POD (%)	36	76	95	100	100	100	100	100

We know the formula,

$$N = \frac{\log_{10}(1-C)}{\log_{10} P}$$

where:

N - is the number of samples

C - is the confidence coefficient

P - is the probability coefficient

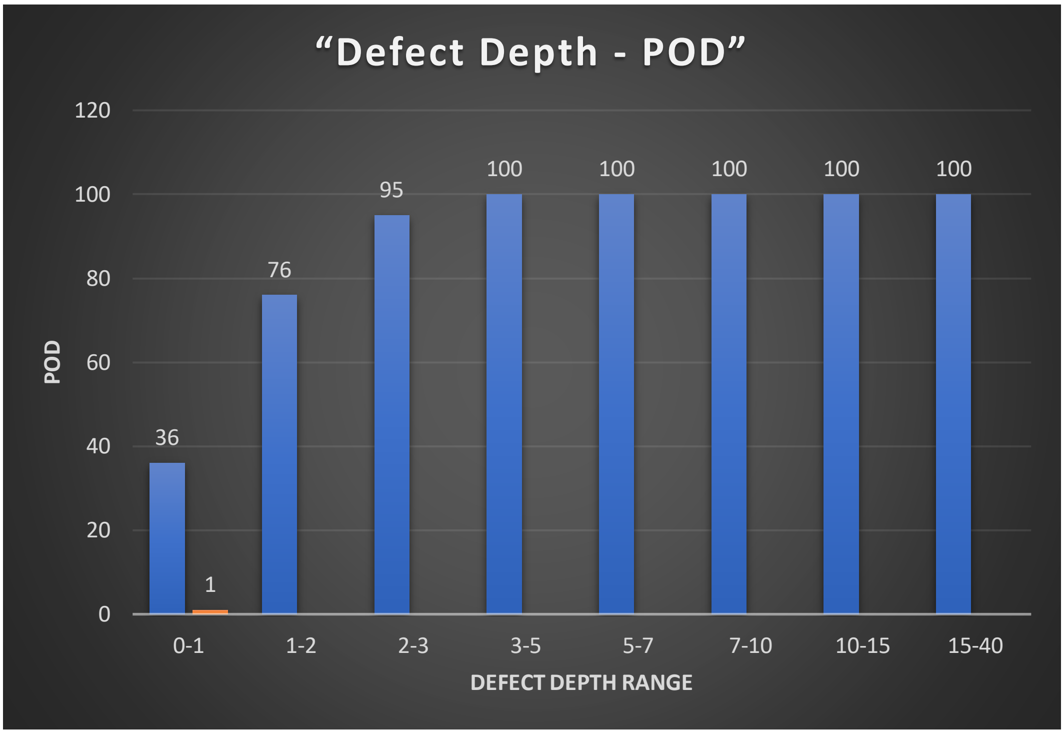

Figure 5. Shows the POD probability with respect to the Defect Depth Range

The 90/95% POD is given, then and , C = 0.95 and P =0.90

Then N equals to,

$$\boldsymbol{N = \frac{\log_{10}(1 - 0.95)}{\log_{10} 0.90}}$$

The number of cycles, N = 28.43 i.e., 29.

N = 29; C = 0.95

By using the formula $C = 1 - P^{29}$

P = 90.18

The chart provided indicates that there can be a maximum of 20 faults in the 2-3 mm range; however, given the current circumstances, the computed number N for 90/95% POD is 29. As a result, fewer samples than are required to satisfy the minimal requirement are available. Thus, portions 2-3 mm and 3-5 mm must be combined.

the flaw detection capability using the alternating current field measurement (ACFM) technique for inspecting cracks in an offshore wind turbine monopile. The physical drivers influencing probability of detection (POD) are reviewed along with variability across materials, locations, and procedures.

ACFM Inspection Method

ACFM is an advanced electromagnetic NDE method specialized for surface-breaking cracks. Sensors induce current flow in the test piece. Perturbations from cracks modify the magnetic field captured using sophisticated processing algorithms. Multi-oriented probes cater to varied geometries.

The technique directly measures depth without length or through-wall sizing. Repeatability helps monitoring small changes. Portability suits offshore work. But surface coatings interfere with signals requiring grinding or sensors above coatings. Costs currently exceed basic methods.

POD Evaluation

POD represents the likelihood of detection across many nominally identical trials under set conditions. This empirical approach captures real-world reliability replacing flawed idealized assumptions.

Of 322 total cracks in a North Sea round robin program, ACFM found 100% for lengths exceeding 20 mm (BV, 2022). interpolating from tabulated results, the detection threshold for 90% POD is 1-2 mm while 95% needs approximately 1.5 mm cracks. This suggests capability to find small defects before reaching critical sizes.

POD Influencing Factors

Numerous interdependent parameters influence NDE reliability:

a) Defect type - morphology, roughness, branching
b) Material properties - thickness, grain structure, permeability
c) Location - curvature, access limitations
d) Orientation - relative to lines of flow
e) Surface finish - coatings, wear, corrosion deposits
f) Coupling medium - paint, marine growths
g) Probe design - frequency, number of axes
h) Testing procedures - scanned coverage, speed
i) Equipment calibration, filters, user training
j) Environmental conditions - visibility, weather, vibration

This multidimensional sensitivity frequently results in shortcomings between laboratory POD quantification on pristine samples versus mix of issues degrading field performance. But trials using realistic defects on retired components in operational settings provide meaningful benchmarks.

Application to Other Materials and Geometries

Unique combinations of machinery structures and damage mechanics demand tailored POD evaluation across the spectrum of offshore assets from wind to oil and gas infrastructure.

Turbine composites suffer manufacturing defects and fatigue cracking. Mooring chains have complex fracture, wear, and corrosion from repeated loading. Pressure vessel integrity matters for pipelines and risers. Anchor chain pile links degrade severely.

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