Fatigue Life Assessment of Underwater Vehicle Pressure Hull due to Corrosion

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ABSTRACT

The operation of underwater vehicles exposes the pressure hull structure to continuous contact with seawater, making corrosion an unavoidable phenomenon. Over time, corrosion degrades the structural integrity of the hull, reducing its fatigue resistance and overall safety. This study investigates the impact of corrosion-induced material thinning, particularly around the penetration areas of the pressure hull, on its structural performance. Using Finite Element Method (FEM) simulation, both corroded and non-corroded hull models are analyzed at an operational depth of 250 meters. The results show that encircling corrosion of penetration hull leads to a 9.93% increase in equivalent stress, a 92.35% reduction in fatigue life, and a 9.04% decrease in Safety Factor (SF). These findings demonstrate a direct relationship between material degradation and structural vulnerability, where reduced wall thickness due to corrosion increases stress concentration, thereby accelerating fatigue damage and reducing the safety margin. This emphasizes the importance of accounting for corrosion effects on the operational aspect of underwater pressure hulls to ensure long-term reliability and safety.

Keywords-fatigue life; underwater vehicle; pressure hull; corrosion

I. INTRODUCTION

Underwater vehicles and other submerged structures depend on the structural integrity of their pressure hulls to withstand extreme hydrostatic pressures in deep-sea environments [1, 2]. However, prolonged exposure to marine conditions results in material degradation due to corrosion, significantly impacting the collapse strength and operational lifespan of these structures [3]. Corrosion-induced thinning weakens the pressure hull, increasing stress concentrations and the risk of failure under operational loads [4]. The detrimental effects of corrosion on fatigue life and structural stability highlight the need for advanced simulations and predictive models to assess the safe operational depth of corroded underwater vehicles [5-7]. Given their critical role in military and commercial applications, understanding corrosion effects on structural performance is essential.

This study addresses the reduction in structural integrity and fatigue life of pressure hulls due to corrosion. While classification standards, such as DNV-GL provide operational safety guidelines, real-world conditions often lead to material degradation beyond design specifications [3, 4]. Corrosion alters stress distribution in critical structural components, reducing safety margins and increasing failure likelihood at greater depths. Although prior studies have examined corrosion effects on fatigue life, many lack comprehensive evaluations of key structural parameters across varying operational depths.

Previous research confirms that corrosion significantly reduces fatigue life and increases stress concentrations in pressure hulls [6, 8]. Expanding on these findings, this study employs an advanced Finite Element Analysis (FEA) to assess how corrosion influences equivalent (von-Mises) stress, fatigue life, and SFs. It is hypothesized that a corrosion-affected pressure hull will exhibit increased equivalent stress, reduced fatigue life, and lower SFs compared to a non-corroded model. This study aims to quantify these effects and determine the maximum safe operational depth for a corroded underwater vehicle. The scope is limited to material thinning in the penetration hull, focusing on key structural parameters influencing operational safety.

II. ANALYTICAL SOLUTION

A. Literature Review

Authors in [9] developed a damage mechanics-based fatigue life model for PMMA cabins, enhancing crack prediction and safety. Authors in [10] found that corrosion reduces submarine hull strength by 6.3%–12.1%, emphasizing the need for precise analysis. Authors in [11] showed that a 30% thickness reduction lowers collapse load by only 6%, highlighting geometric effects. Authors in [12] demonstrated that high hydrostatic pressure accelerates corrosion in low-alloy steels, requiring protective measures. Authors in [13] found that weld seams affect stress distribution, with fatigue life stabilizing at 40 MPa for 49 years. Authors in [4] estimated HY-80 corrosion at 0.17–0.18 mm/year, reducing diving depth by ~2.7 m/year. Meanwhile, authors in [14] found a 0.014 mm/year corrosion rate in a Japanese midget submarine at 406.7 m depth, reducing hull thickness by 11% in 61 years. Authors in [6] demonstrated that corrosion decreases collapse pressure by 20% and yield pressure by 40%. Authors in [15] emphasized the need to optimize the structural strength formula for ring-stiffened cylinders to tailor pressure hull designs for specific operations. Authors in [16] predicted the fatigue life of a HY-80 submarine pressure hull using FEM analysis and the Palmgren-Miner rule, estimating a 29-year lifespan with an SF of 2.5.

Authors in [17] stated that the submarine construction testing method using FEA can serve as a basis for optimizing scantling calculations. Several studies confirm that FEA effectively predicts pressure hull strength under corrosion effects. [18-20] Gannon's FEA simulations show a 3%–19% increase in collapse pressure in corroded hull areas with penetrations and castings. In [21-22], it was found that FEA-based pressure simulations on a pressure hull with low-accuracy modeling resulted in a simulation accuracy of only 6%. However, no research has specifically assessed fatigue life reduction due to corrosion in submarine pressure hulls.

B. Methodology for Analysis

This study investigates corrosion's impact on the fatigue strength of underwater vehicle pressure hulls. A 3D model is developed, with a second model simulating circumferential corrosion around the penetration region. Stress and fatigue life analyses compare structural integrity in original and corroded conditions. The findings offer insights into structural degradation and safe operation. The research flow is illustrated in Figure 1.

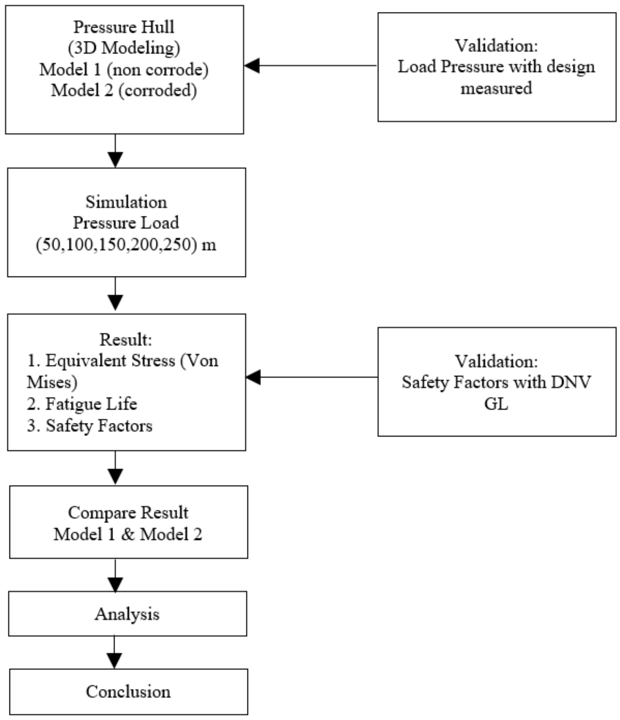

Fig. 1. Methodology for analysis flow chart.

C. 3D Modeling

Three dimensional (3D) modeling was conducted using software to create two models: a corrosion-free pressure hull (Model 1) and a corrosion-affected hull (Model 2). Corrosion was simulated as 2 mm thinning, represented by 4 mm diameter circles intersecting the penetration and hull. The pressure hull modeling is depicted in Figures 2 and 3.

D. Meshing

Meshing ensures FEA accuracy by optimizing element count while considering hardware limits. The results are displayed in Table I and Figure 4.

E. Validation

Validating an underwater vehicle through physical experiments is impractical. This study uses FEA tools for modeling-stage validation, assessing compressive load via equivalent stress design and SFs per DNV-GL standards.

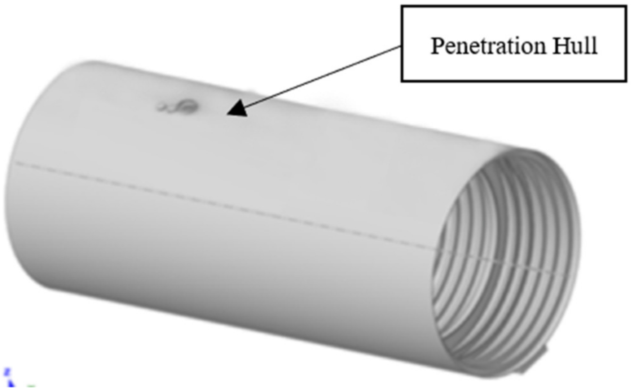

Fig. 2. Pressure hull 3D modeling.

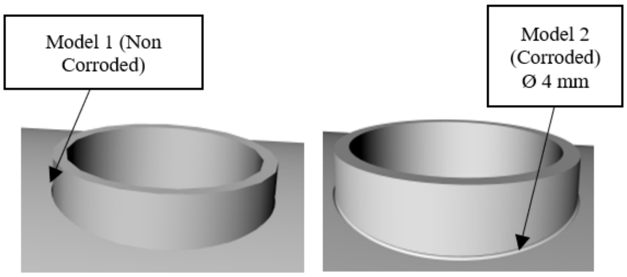

Fig. 3. Detailed penetration hull modeling.

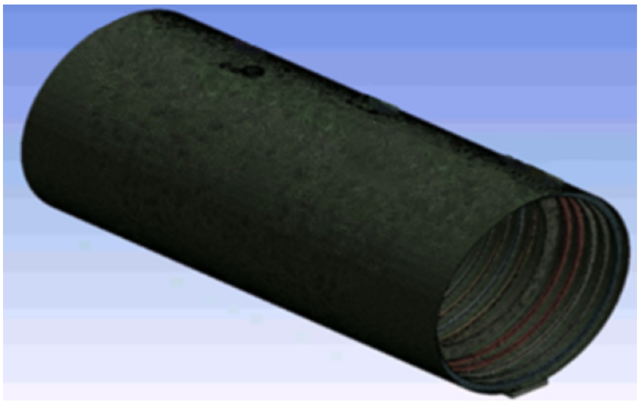

Fig. 4. Meshing process for pressure hull modeling.

TABLE I. MESHING PROCESS RESULTS

Mesh parameters	Model 1	Model 2
Total elements	403,339	853,161
Total nodes	804,900	1,460,064
Min. element size (mm)	50	5
Max. element size (mm)	100	100
Adaptive sizing	Yes	Yes

1) Pressure Load Simulation

The validation of the hydrostatic load simulation results will be performed utilizing test information data. The data used for validating pressure loads and their values are outlined in Table II.

TABLE II. REFERENCE DATA FOR PRESSURE LOAD VALIDATION.

A. Equivalent stress at shell (MPa)	
Mid bay membrane	397.1625
Mid bay outer side	469.9755
Mid bay inner side	344.3912
Frame membrane	399.1572
Frame outer side	328.4961
Frame inner side	511.7895
B. Absolute pressure at crush depth 550 m (MPa)	5.632

The pressure loads are set based on the absolute pressure at depths of 50–250 m, being applied to the outer hull surface, and excluding supports. The load pressure parameters are detailed in Table III. Equation (1) was considered :

$$P_{abs} = P_{load} + P_{atm} \quad (1)$$

where $Pabs$ = Absolute pressure, P_{load} = Load pressure = 101,325 Pa (standard assumption), and P_{atm} = Atmospheric / gauge pressure

TABLE III. LOAD PRESSURE PARAMETERS

h (m)	P_h (Pa)	P_h (MPa)	P_{abs}
50	502,762.50	0.503	0.604
100	1,005,525.00	1.006	1.107
150	1,508,287.50	1.508	1.610
200	2,011,050.00	2.011	2.112
250	2,513,812.50	2.514	2.615

2) Safety Factor

DNV-GL (2018) requires 10,000 load cycles and minimum SFs for depths of 50–250 m. The simulations confirm compliance, as shown in Table IV.

TABLE IV. SF CRITERIA FOR PRESSURE HULL CONSTRUCTION (DNV-GL, 2018)

Nominal diving pressure (bar)	10	20	30	40	50	> 60
S_2	2.4	2	1.87	1.8	1.76	1.73

According to the classification regulations, the minimum SF value for pressures between 5-60 bar can be calculated using the following approximation formula:

$$S_2 = \frac{8}{\text{NDP}} + 1.6 \quad (2)$$

where S_2 = SF at pressure 5-60 bar and NDP = Nominal Diving Pressure (bar).

The simulated SF can be calculated using (3) for comparison with DNV-GL standards:

$$\text{SF} \frac{\sigma_{max}}{\sigma_{allowable}} \quad (3)$$

where σ_{max} = the highest stress value from the simulation results and $\sigma_{allowable}$ = the maximum stress value of the material (following yield stress).

3) Output Analysis

The simulation assessed pressure load effects on original and corroded models, equivalent stress, fatigue life, and SFs using FEA software and based on DNV-GL standards.

III. SIMULATIONS RESULTS

A. Model 1

Model 1 represents a pressure hull with a penetration, free of corrosion. The simulation followed predefined parameters, with the results being analyzed, accordingly.

1) Equivalent Stress (Von-Mises)

The highest von-Mises stress (280.61 MPa) occurs at the penetration component at 250 m depth, remaining below HY-80's yield stress. The results are presented in Table V.

TABLE V. EQUIVALENT STRESS (VON-MISES) MODEL 1

Depth (m)	Pressure load (MPa)	Min. equivalent stress (MPa)	Max. equivalent stress (MPa)
50	0.604	3.63E-03	166.16
100	1.107	6.54E-03	216.54
150	1.610	9.32E-03	239.13
200	2.112	1.21E-02	264.42
250	2.615	1.49E-02	280.61

2) Fatigue Life Values (Gerber and Soderberg Methods)

The minimum fatigue life at 250 m is 142,113 cycles (Soderberg), exceeding the DNV-GL limit. Soderberg is more conservative due to its yield strength basis. The obtained values are portrayed in Table VI.

TABLE VI. FATIGUE LIFE MODEL 1

Depth (m)	Load pressure (MPa)	Min. fatigue life-Gerber (cycles)	Min. fatigue life-Soderberg (cycles)	Pressure load ratio
50	0.604	1,000,000	1,000,000	0.26
100	1.107	1,000,000	1,000,000	0.14
150	1.610	1,000,000	1,000,000	0.10
200	2.112	1,000,000	325,330	0.08
250	2.615	1,000,000	142,113	0.06

3) Safety Factor Values (DNV-GL 2018)

The simulated stress values meet the DNV-GL standards for 50–250 m depths, confirming Model 1's compliance with them. The SF values for each simulation load are listed in Table VII.

TABLE VII. SF MODEL 1.

Depth (m)	Load Pressure (MPa)	Load Pressure (bar)	SF Minimum as DNV-GL	SF Calculation
50	0.604	6.04	2.92	3.31
100	1.107	11.07	2.32	2.54
150	1.610	16.10	2.10	2.30
200	2.112	21.12	1.98	2.08
250	2.615	26.15	1.91	1.96

B. Model 2

Model 2 represents the pressure hull with penetration, incorporating the effects of corrosion was simulated based on the parameters outlined in the previous subsection.

1) Equivalent Stress (Von-Mises)

The maximum von-Mises stress at the penetration is 287.92 MPa at 250 m, below HY-80's yield stress, as seen in Table VIII.

TABLE VIII. EQUIVALENT STRESS (VON-MISES) MODEL 2.

Depth (m)	Pressure load (MPa)	Min. equivalent stress (MPa)	Max. equivalent stress (MPa)
50	0.604	3.63E-03	166.16
100	1.107	6.54E-03	216.54
150	1.610	9.32E-03	239.13
200	2.112	1.21E-02	264.42
250	2.615	1.49E-02	280.61

2) Fatigue Life Values (Gerber and Soderberg Methods)

The minimum fatigue life at 250 m is 142,113 cycles (Soderberg), exceeding the DNV-GL limit. Soderberg is more conservative due to its yield strength basis, as illustrated in Table IX.

TABLE IX. FATIGUE LIFE MODEL 2.

Depth (m)	Load pressure (MPa)	Min. fatigue life-Gerber (cycles)	Min. fatigue life-Soderberg (cycles)	Pressure load Ratio
50	0.604	1,000,000	1,000,000	0.26
100	1.107	1,000,000	549,370	0.14
150	1.610	1,000,000	267,342	0.10
200	2.112	600,000	43,211	0.08
250	2.615	180,000	10,877	0.06

3) Safety Factor Values (DNV-GL 2018)

The SF values for each simulation load for Model 2 are shown in Table X.

TABLE X. SF MODEL 1

Depth (m)	Load pressure (MPa)	Load pressure (bar)	SF minimum as DNV-GL	SF calculation
50	0.604	6.04	2.92	3.31
100	1.107	11.07	2.32	2.54
150	1.610	16.10	2.10	2.30
200	2.112	21.12	1.98	2.08
250	2.615	26.15	1.91	1.96

IV. SIMULATIONS RESULTS

A. Equivalent Stress (Von-Misses)

Model 2's maximum equivalent stress rises by 9.93% due to corrosion but remains below HY-80's yield limit at 250 m, as depicted in Figure 5 and Table XI.

TABLE XI. EQUIVALENT STRESS MODELS 1 AND 2

Depth (m)	Load pressure (MPa)	Model 1 (MPa)	Model 2 (MPa)	Diff.
50	0.604	166.16	176.21	6.04%
100	1.107	216.54	229.67	6.07%
150	1.610	237.07	253.64	6.99%
200	2.112	250.00	277.78	9.11%
250	2.615	261.90	287.92	9.93%

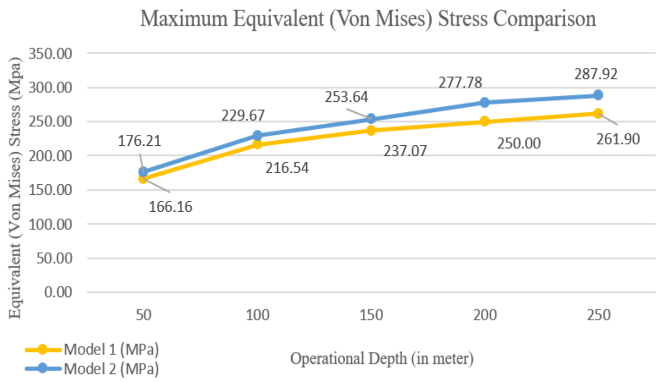

Fig. 5. Comparison of maximum equivalent stress (von-Mises): models 1 and 2.

B. Fatigue Life (Soderberg)

Figure 6 and Table XII show a 92.35% fatigue life reduction in Model 2 at 250 m due to corrosion. Based on Soderberg theory, the corroded hull meets the DNV-GL 2018 minimum, allowing operation at 250 m.

TABLE XII. FATIGUE LIFE MODELS 1 AND 2

Depth (m)	**Load pressure (MPa)**	**Model 1 (cycles)**	**Model 2 (cycles)**	**Diff.**
50	0.604	1,000,000	1,000,000	0.00%
100	1.107	1,000,000	549,370	45.06%
150	1.610	1,000,000	267,342	73.27%
200	2.112	325,330	43,211	86.72%
250	2.615	142,113	10,877	92.35%

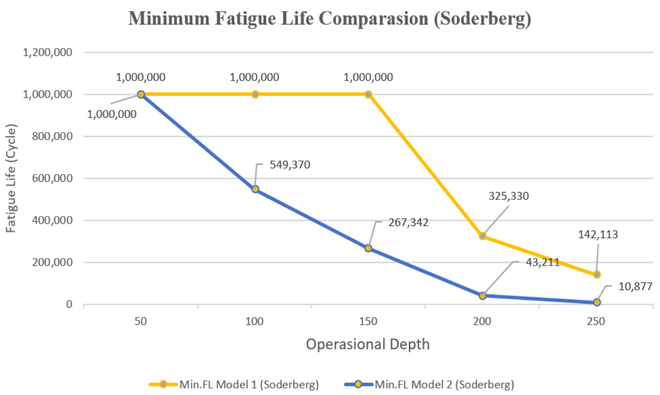

Fig. 6. Comparison of minimum fatigue life models 1 and 2.

C. Safety Factors

Figure 7 and Table XIII demonstrate a 9.04% SF reduction in Model 2 due to corrosion, increasing stress and weakening structural integrity. Model 1 meets DNV-GL 2018 criteria of up to 250 m, while Model 2 reaches the critical threshold of 150–250 m.

In Tables XIV and XV, the key parameters, namely depth, pressure load, maximum von-Mises stress, minimum fatigue life (Soderberg theory), and SF (DNV-GL) are summarized. The criteria are marked as "PASS" or "FAIL" for Model 1 (non corroded) and Model 2 (corroded):

TABLE XIII. SF MODELS 1 AND 2

Depth (m)	**Load pressure (MPa)**	**SF minimum as DNV-GL**	**SF model 1**	**SF model 2**	**Diff.**
50	0.604	2.92	3.31	3.12	5.70%
100	1.107	2.32	2.54	2.39	5.72%
150	1.610	2.10	2.32	2.17	6.53%
200	2.112	1.98	2.20	1.98	9.00%
250	2.615	1.91	2.10	1.91	9.04%

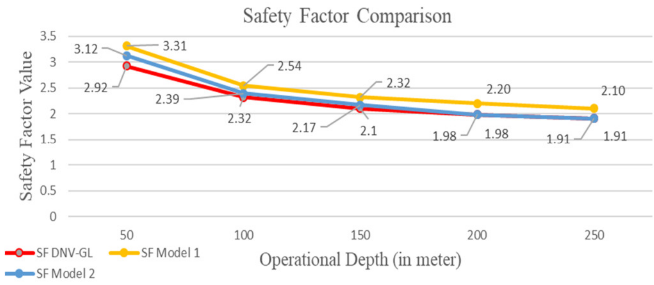

Fig. 7. SF comparison: models 1 and 2.

TABLE XIV. KEY PARAMETER SUMMARY FOR MODEL 1

Depth (m)	**Load pressure (MPa)**	**Max. equivalent (von-Mises) stress**	**Min. fatigue life (Soderberg)**	**SF**
50	0.604	PASS	PASS	PASS
100	1.107	PASS	PASS	PASS
150	1.610	PASS	PASS	PASS
200	2.112	PASS	PASS	PASS
250	2.615	PASS	PASS	PASS

TABLE XV. KEY PARAMETER SUMMARY FOR MODEL 2

Depth (m)	**Load pressure (MPa)**	**Max. equivalent (von-Mises) stress**	**Min. fatigue life (Soderberg)**	**SF**
50	0.604	PASS	PASS	PASS
100	1.107	PASS	PASS	PASS
150	1.610	PASS	PASS	PASS
200	2.112	PASS	PASS	PASS
250	2.615	PASS	PASS	PASS

Based on the data analysis conducted for all simulations on Model 1 (non-corroded) and Model 2 (corroded), it was found that the pressure hull with corroded penetration areas remains operable at a depth of 250 meters, despite the observed effects of corrosion on equivalent stress, fatigue life, and SF.

V. DISCUSSION

Previous research has mainly focused on corrosion's effect on structural strength, but not on fatigue performance. This study addresses that gap by analyzing fatigue life in corroded pressure hulls, especially at penetration areas. At 250 meters with 2.615 MPa pressure, equivalent stress increased by 9.93% in the corroded model, reaching 287.92 MPa due to wall thinning and stress concentration.

The fatigue life analysis using the conservative Soderberg approach showed significant degradation. In the non-corroded model, the fatigue life was 142,113 cycles, but it dropped to 10,877 cycles in the corroded model, representing a 92.35% reduction. Corrosion in penetration areas amplifies cyclic stress, causing early crack initiation and faster propagation. These results demonstrate that fatigue performance is severely affected even at operational depths.

The SF also declined from 2.10 in the non-corroded model to 1.91 in the corroded one. Although this meets the DNV GL minimum requirement, it shows a reduced margin of safety. Considering that the crush depth pressure is 5.632 MPa, corrosion already causes structural vulnerability at less than half that depth, emphasizing the need for inspection and fatigue monitoring in hull design.

VI. CONCLUSION

This study quantified corrosion effects on a 250m-depth pressure hull, revealing critical structural impacts. The corroded penetration areas exhibited 9.93% higher equivalent stress due to wall thinning and stress concentration. More critically, fatigue life decreased by 92.35% as corrosion pushed stresses beyond Soderberg safe limits. While the Safety Factor (SF) remained at acceptable limits (1.91, 9.04% reduction), the results identified corrosion as a key integrity concern for deep-sea operations.

This study presents original scientific evidence on corrosion-depth interactions, was previously uncharacterized in underwater vehicle design. The findings challenge conventional safety assessments by demonstrating how corrosion-fatigue synergy particularly compromises penetration areas - a significant advance for marine engineering practice.

The present work's novelty lies in that it provides the first quantitative analysis of corrosion-depth interactions in underwater vehicle penetrations, revealing how corrosion geometry amplifies hydrostatic stress effects. Unlike previous studies on intact hulls or shallow corrosion, the study demonstrates: (1) validated stress-corrosion-fatigue relationships for deep-diving conditions, (2) limitations of standard SFs, and (3) the critical need for enhanced corrosion protection in penetration zones.

For future research, it is proposed to investigate advanced coating systems and real-time monitoring approaches for penetration areas, as this study's results confirm these locations as critical vulnerability zones in deep-sea operations. The methodology developed in this work can be extended to other pressure vessel applications, where corrosion and cyclic loading coexist.

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