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ENHANCING OFFSHORE PIPELINE LAYING SAFETY: A RISK-BASED SYSTEMIC APPROACH TO WIRE ROPE FAILURES IN BUCKLE DETECTORS USING ADVANCED MATERIAL SOLUTIONS

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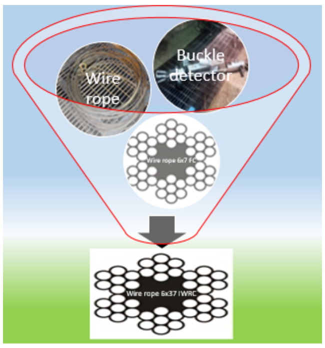
Graphical abstract



Abstract

Wire rope failure in a buckle detector during offshore piping laying work can cause operational downtime, and significant safety risks. This article analyzes the causes of wire rope breakage with a diameter of 12 mm and Improved Plow Steel (IPS) grade used in the buckle detector. The analysis method includes a risk-based systemic approach, including Root Cause Analysis (RCA) and Failure Mode and Effects Analysis (FMEA). Failure data during simulation shows that the FC 6x7 wire rope construction experienced ten failures, the IWRC 6x19 experienced five failures, and the IWRC 6x37 experienced only two failures. The analysis results show that the main failure factors include material fatigue, overloading, and corrosion due to the offshore environment. Improvement recommendations include replacing the current FC 6x7 construction wire rope with IWRC 6x37, offering higher tensile strength, flexibility, and superior fatigue and corrosion resistance. This article contributes to improving the reliability of the buckle detector system and reducing the risk of failure in offshore work.

Keywords: Wire rope, buckle detector, offshore laying piping, RCA, FMEA

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1. Introduction

Offshore pipe laying activities involve using barges (unique vessels) equipped with equipment to install pipes on the seabed. This process involves several stages, starting from the preparation of the pipe, namely the pipe is prepared on land and transported to the barge using a ship. Then the pipe is welded on the barge to form a strong connection. Then, the pipe is installed and lowered to the seabed using a tensioner and stinger system installed on the barge. Simultaneously, monitoring and detection are carried out with a buckle detector used to monitor deformation or damage to the pipe during the installation process. Finally, testing and commissioning are done after installation, and the pipe is tested to ensure structural and functional integrity [1], [2].

The buckle detector is equipped with wire rope that withstands dynamic loads and ensures the stability of the system during operation. Therefore, the wire rope on the buckle detector is a critical component.

However, it is not uncommon for wire rope failures, such as breaking, to cause operational disruptions, increased costs, and safety risks [3],[4].

It should be noted that wire rope consists of several steel wires twisted into strands, then several strands are twisted again into one unit. Wire rope is used because of its high tensile strength, flexibility, and resistance to dynamic loads. However, wire rope is susceptible to failure due to material fatigue, corrosion, and overload. Common types of wire rope construction include Fiber Core (FC) 6x7, Independent Wire Rope Core (IWRC) 6x19, and IWRC 6x37. Each type has different characteristics regarding tensile strength, flexibility, and resistance to fatigue and corrosion [5=7].

Several previous studies have discussed various aspects of wire rope, including the causes of failure, early detection methods, and the development of new materials. Corrosion can significantly reduce the tensile strength of wire rope, especially in areas directly exposed to the marine environment [8], [9]. Milone and Mazurek reviewed the fatigue assessment methodology of corroded wire rope, concluding that material fatigue, corrosion, and dynamic loads are the leading causes of wire rope failure [10], [11]. On the other hand, Peng et al. analyzed friction and wear in wire rope, especially in hoisting applications. They found that friction between wires in a wire rope can cause significant wear, especially in areas experiencing high dynamic loads [12]. Feng and Wang evaluated the performance of wire rope against lateral loads, which are common in offshore applications. They concluded that wire ropes with denser construction, such as IWRC 6x37, have better resistance to lateral loads [13]. Hu et al. evaluated the failure of wire ropes on offshore equipment, focusing on the effect of additional torsional loads on fatigue behavior. They found that torsional loads can accelerate wire rope failure, especially in areas experiencing high friction [14].

Several researchers have also tried to develop early detection methods for wire rope damage. Zhang et al. proposed a wire rope damage detection method based on visual sensors, which can identify wire rope surface damage in real-time [15]. Liu et al. developed a wire rope damage detection method based on Magnetic Flux Leakage (MFL) signal analysis and artificial neural networks (1D-CNNs), which can detect internal wire rope damage with high accuracy [16]. In addition, Li et al. proposed using a new material for wire ropes, namely high-strength stainless steel wire rope (HSSSWR), which is claimed to have better resistance to corrosion and fatigue [17]. Meanwhile, Salah et al. focused on optimizing wire robot-based automatic storage and retrieval systems in industrial environments, using Failure Mode and Effects Analysis (FMEA) analysis to improve reliability. However, this study does not explain the risk of further failure or compare the wire rope performance [18].

Based on a review of previous studies, it can be concluded that research related to wire rope focuses more on corrosion as conducted by Chen et al., Yang et al. [8],[9], and Milone et al., Mazurek [10],11]. Friction and wear as analyzed by Peng et al. [12]. Loads on wire ropes as evaluated by Feng and Wang and Hu et al. [13], [14]. Early detection of damage as developed by Zhang et al. and Liu et al. [15],[16]. Development of new materials as proposed by Li et al. [16]. Only Salah et al. focused on increasing reliability using the FMEA method. However, this study does not explain the risk of failure in depth or compare the wire rope performance.

Therefore, the researcher will conduct this study using a risk-based systemic approach that includes Root Cause Analysis (RCA) and Failure Mode and Effect Analysis (FMEA) to fill the research gap and provide new contributions to the literature. In addition, this study compares three types of wire ropes (FC 6x7, IWRC 6x19, and IWRC 6x37) with failure data during the survey, providing more substantial data-based recommendations. This study analyzes wire rope failures on buckle detectors in the context of offshore pipeline installation, which has not been widely explored in the literature. Thus, this study aims to provide a more comprehensive and measurable solution to reduce the risk of wire rope failures on buckle detectors. The contribution of this study is a risk-based systemic approach using RCA and FMEA to identify root causes of failure and systematically evaluate risks. Then, the performance of wire ropes covering three types of wire ropes (FC 6x7, IWRC 6x19, and IWRC 6x37) was compared with failure data during the study. With this contribution, this study is expected to fill the gap in the literature and provide a more effective solution to reduce the risk of wire rope failure in buckle detectors.

2. Material and Method

2.1. Material RCA and FMEA Theory

1. Root Cause Analysis (RCA):

RCA is a systematic method for identifying the root cause of a problem. RCA is used in the context of wire rope to find the root cause of failure, such as material fatigue, overloading, and corrosion. This method involves collecting data, analyzing evidence, and identifying factors contributing to the failure [19].

2. Failure Mode and Effects Analysis (FMEA) :

FMEA is a risk analysis technique for identifying failure modes, their causes, and their impact on a system. It helps prioritize risks based on Severity (S), Occurrence (O), and Detection (D), which are then used to calculate the Risk Priority Number (RPN). In the context of wire rope, FMEA is used to evaluate the risk of failure and design corrective actions [20], [21].

Scale Description FMEA:

- Severity (S) : 1 (no effect) to 10 (severe effect).
- Occurrence (O) : 1 (very rare) to 10 (very frequent).
- Detection (D) : 1 (straightforward to detect) to 10 (challenging to detect).
- Risk Priority Number (RPN) : Calculated using RPN

$$RPN = S \times O \times D. \quad (1)$$

2.2 Method

The analysis was conducted using a risk-based systemic approach, which includes:

1. Root Cause Analysis (RCA): Used to identify the root cause of wire rope failure.
2. Failure Mode and Effects Analysis (FMEA): Used to evaluate failure modes and their impact on the system.
3. Wire Rope Performance Comparison: Comparing three types of wire rope with a diameter of 12 mm and IPS grade, namely FC 6x7, IWRC 6x19, and IWRC 6x37.

Data is collected from field inspections, failure reports, and equipment technical specifications.

3. Result and Discussion

A. Result

3.1. Wire Rope Failure Data

The data collection results in the table show that three types of steel cables, namely FC 6x7, IWRC 6x19, and IWRC 6x37, perform well. This data includes various types of failures and the average downtime generated. This analysis can help understand each kind of cable's performance and determine the most optimal choice for a particular application. The following is the wire rope failure data for the three types of wire rope:

Table 1. Wire rope failure data for the three types of wire rope

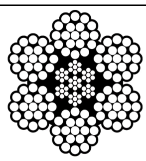
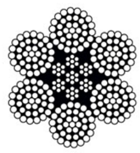
Parameter	FC 6x7	IWRC 6x19	IWRC 6x37
Construction			
Total Failure	10	5	2
Total Disconnect Failure	3	0	0
Partial Disconnect Failure	2	1	0
Crack Failure	2	1	1
Corrosion Failure	3	2	0
Wear/Abrasion Failure	2	1	1
Average Downtime	5.4 hours	2.5 hours	1 hour

Figure 1. Buckle detector

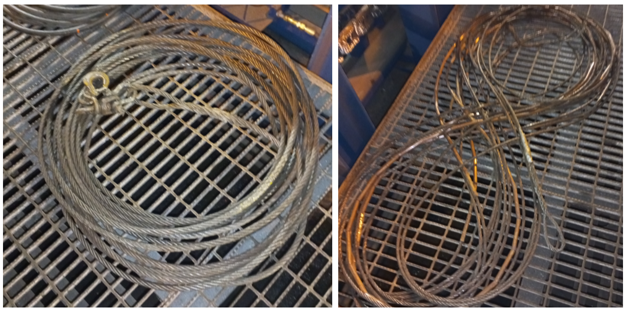


Figure 2. New wire rope

Figure 3. Wear and crown break wire rope

Figure 4. Total failure of wire rope

From the data above, it can be concluded that the IWRC 6x37 cable offers the best performance regarding reliability, resistance to various failures, and downtime efficiency. Meanwhile, the FC 6x7 cable tends to be more prone to failure and has a more extended downtime. The selection of cables should be adjusted to the needs of the application and the operational environment to ensure optimal performance.

3.2. Root Cause Analysis (RCA)

Based on the data and investigations that have been carried out, several root causes of wire rope failures and their impacts can be identified. This analysis aims to understand the factors contributing to failure and provide recommendations for improvements to improve the reliability and performance of wire ropes in operations. By addressing these root causes, it is hoped that the risk of failure and operational efficiency can be reduced. Based on RCA, several factors were found to cause wire rope to break:

Table 2. RCA found several factors that cause wire rope to break

No.	Root Cause	Supporting Evidence/Data	Impact	Recommendations for Improvement
1	Material fatigue due to cyclic loading	Micro cracks in wire rope were found during visual inspection and microscopic tests.	The crack develops into a macro crack, causing the wire rope to break.	Replace the wire rope with a more fatigue-resistant type (e.g., IWRC 6x37).
2	Overload during operation	Operational reports show the load exceeding the wire rope capacity.	Excessive stress causes premature failure of wire rope.	Conduct operator training and add a load monitoring system.
3	Corrosion due to offshore environment	Corrosion tests showed a decrease in the tensile strength of wire rope due to exposure to sea water.	Wire rope becomes brittle and prone to failure.	Use wire rope with anti-corrosion coating or a more corrosion-resistant material.
4	Operational procedure error	Investigations showed the operator did not follow SOP when operating the buckle detector.	Overloading and improper use accelerate failure.	Improve SOP and conduct retraining for operators.
5	Lack of inspection and maintenance	There is no record of wire rope inspection in the last 6 months.	Damage is not detected early, leading to sudden failure.	Regular inspections and preventive maintenance are performed as scheduled.

From the analysis results, it can be concluded that various factors, including material fatigue, excessive load, corrosion, operating procedure errors, and lack of inspection and maintenance, caused the failure of the wire rope. Recommendations for improvement such as using more substantial materials, operator training, implementing a load monitoring system, and improving inspection and maintenance procedures must be implemented immediately. It is hoped that the reliability of the wire rope can be improved, thereby reducing unexpected downtime.

3.2. Failure Mode and Effects Analysis (FMEA)

Based on the Failure Mode and Effects Analysis (FMEA), several failure modes can be identified in the main components along with their potential causes, impacts, and risk levels. This analysis aims to evaluate the risk of failure and provide recommendations for corrective actions to reduce the possibility of failure and its impact on operations, and safety. By understanding these risk factors, more effective preventive measures can be implemented. Here is the FMEA table:

Table 3. FMEA and recommendation action

No.	Component	Failure Mode (Failure Mode)	Potential Causes	Effect/Impact	Severity (S)	Occurrence (O)	Detection (D)	(RPN)	Recommended Actions
1	Wire Rope	Separated	Material fatigue due to cyclic loading	Operational downtime, equipment damage, worker safety risks	9	8	4	288	Replace with IWRC 6x37 wire rope which is more fatigue resistant.
2	Wire Rope	Separated	Overload during operation	System failure, increased repair costs	8	7	5	280	Conduct operator training to avoid overloading.
3	Wire Rope	Separated	Corrosion due to offshore environment	Decreased tensile strength, risk of sudden failure	9	9	3	243	Use wire rope with an anti-corrosion coating (e.g., galvanized or stainless steel).
4	Buckle Detector	Failed to detect pipe deformation	Sensor or electronic system failure	Pipe damaged during installation,	10	6	6	360	Perform periodic calibration and inspection on the

No.	Component	Failure Mode (Failure Mode)	Potential Causes	Effect/Impact	Severity (S)	Occurrence (O)	Detection (D)	(RPN)	Recommended Actions
				risk of accident					buckle detector system.
5	Operating System	Overloading	Operational procedure error	Excessive load on wire rope, risk of breaking	8	7	5	280	Improve operational procedures and add load monitoring systems.

From the FMEA analysis results, it can be seen that several components such as wire rope and buckle detector have a significant risk of failure, mainly due to material fatigue, overload, corrosion, and operational procedure errors. Recommendations for corrective actions, such as using more resistant materials, operator training, and improvement of monitoring and inspection systems, need to be implemented immediately to reduce the RPN value and improve system reliability. By implementing these steps, it is hoped that the risk of failure can be minimized, so that operations can run more safely, efficiently, and economically.

B. Discussion

Based on the data presented regarding wire rope failures, a performance comparison can be seen between three types of wire ropes: FC 6x7, IWRC 6x19, and IWRC 6x37. This analysis aims to understand the failure rate and average downtime generated by each type of wire rope so that solutions can be identified to improve operational efficiency. The following is a comparison of the three wire ropes analyzed.

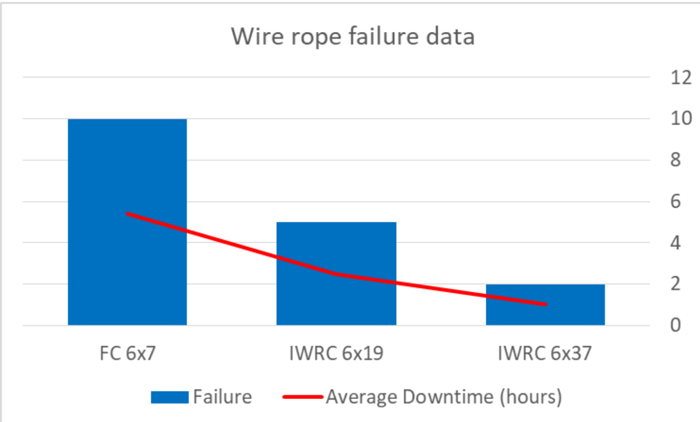


Figure 5. Failure frequency and average downtime per wire rope type

Based on the results of the analysis, it can be concluded that the wire rope breakage at the buckle detector was caused by a combination of mechanical factors (material fatigue and overload) and environmental factors (corrosion). The harsh offshore environment accelerates the material degradation process, while dynamic loads during operation worsen the condition of the wire rope. Replacing wire rope from FC 6x7 to IWRC 6x37 or IWRC 6x19 can improve the reliability of the buckle detector system. IWRC 6x37 offers the best tensile strength, flexibility, fatigue resistance, and abrasion/corrosion resistance. Replacing the wire rope can significantly reduce the risk of wire rope breaking

4. Conclusion

Wire rope breakage on buckle detector during offshore piping laying work is a serious problem that requires in-depth analysis. The main factors causing failure include material fatigue, overloading, and corrosion. Recommendations for repair include:

1. Wire Rope Replacement: Replace FC 6x7 with IWRC 6x37 or IWRC 6x19.
2. Preventive Maintenance: Perform periodic inspections and preventive maintenance.

3. Operator Training: Provide training to avoid overloading during operation.
4. Design Optimization: Consider wire rope designs that are more resistant to dynamic loads and corrosion.

Implementing these recommendations is expected to reduce the risk of wire rope failure and increase the reliability of the buckle detector system. Based on the results of the analysis and findings in this study, here are some recommendations for further research that can be carried out to understand better and overcome the problem of wire rope failure on the buckle detector during offshore piping laying work: Further research can focus on the development of more corrosion and fatigue resistant wire rope materials, design optimization, implementation of real-time monitoring systems, and more in-depth offshore environmental impact analysis. This approach is expected to reduce the risk of wire rope failure and increase the reliability of the buckle detector system in offshore piping laying work.

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