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Structural integrity monitoring: Review of the last 10 years of technological development for offshore oil & gas platforms

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Abstract

The majority of offshore platforms have passed their design lives. The ageing related problems and how to manage these problems is key concern for oil and gas offshore structures. For this reason, offshore structures, especially fixed jacket platforms, should be appropriate conditions for their intended use through their service life. The need to maintain offshore structural integrity has been increased in recent years and plays a significant role in continuous integrity and life extension. Early detection of damaged items can prolong the life of platforms by replacing them and results in reducing maintenance expenses and increasing safety. Therefore, SI monitoring techniques, especially non-destructive techniques (NDT), are widely used for the early detection of damage in offshore structures.

The purpose of this thesis is to analyze the last decade (2010-2021) of technological development within SI monitoring techniques and how these techniques can be used to increase the structural integrity of oil & gas platforms. There is an exhaustive report called “Structural Integrity Monitoring: Review and appraisal of current technologies for offshore application”, However, it was published more than 10 years, and new work is needed to be performed for the structural integrity of platforms. Therefore, the objective of this thesis is to serve as an overall update of existing techniques, both already-existing techniques that further developed in the last 10 years and new proposals as well. In this work, more than 70 papers, books and articles are reviewed to get the most applicable Structural integrity monitoring techniques in the offshore industry. This study will also discuss the concept for monitoring existing ageing jacket platforms in more detail.

There are five chapters in this study work: Introduction, five chapters with 2 case studies, conclusions with the future recommendation, two appendices. The first chapter is included a literature survey of current SI monitoring in offshore structures, SI management, codes, applicable standards and a brief description of offshore structures’ design.

The fundamental information about potential loads, damage characteristics and failure modes of the jacket structures is then clarified in Chapter 2.

Chapter 3 provides a qualitative review of SI monitoring techniques mainly used for damage detection, the position of floating structures as well as advantages, limitations, monitoring capabilities, maturity in the offshore industry, requirements for use and probability of detection (PoD) of these techniques.
Chapter 4 describes the development of SI monitoring techniques for critical items in offshore platforms for the extension of their service lives. Specific case studies related to proper SI monitoring techniques selection in the jacket platform of the Caspian Sea and proper localization of Acoustic emission sensors in offshore jacket platform are presented in the last chapter. Conclusion and two appendices are also generated in this thesis.

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Introduction

The majority of offshore structures worldwide are reaching or are beyond their design lives. The expected life for offshore structure platforms is not so precise. However, the design life is predicted to be between 20 to 25 years depending on excessive loads, for example, environmental loads including wave, current loads, and impact loads during lifetime. These loads cause fatigues, cracks, corrosion and other essential damages in structures. Such ageing structures should always be under supervision and extensively maintained to decrease the possibility of damage from early stages that could result in loss of integrity. This can be achieved by developing robustness, accuracy, efficiencies and cost-effectiveness that allow data collection about the condition of the platform [1].

Almost half of the North Sea offshore platforms are approaching or have already passed their design life and creating complicated problems for the SI management of these platforms [2]. Therefore, there is a requirement for SI Monitoring techniques to increase certainty in structural integrity and to minimize inspection expenses. With SI monitoring techniques, structures can be inspected over an interval using various measurements, providing information about the offshore platforms' structural integrity, safety, and reliability [3].

Non-Destructive Testing (NDT) is one of the engineering fields that deals with all techniques for detecting and analyzing discontinuities. Detects in the materials and structures can influence their structural integrity and compatibility. Therefore, NDT is essential for ensuring safe operation, quality management and evaluating the life of the structure. The detects can cause cracks in offshore structures, especially in the welds and can lead to decreased material strength and loss of integrity. Therefore, NDT methods' importance allows inspection of materials and structures without demolishing their original nature and integrity [4]. The choice of technique depends on plenty of parameters, properties of the material, type of failures which are presented in Chapter 3.

The objective of this thesis is a literature review of structural integrity monitoring (SIM) topic, available codes and standards which can be used as a reference for SI monitoring, assessment of failures, consequences and appropriate SIM techniques to detect these failure modes in the last ten years. The description of SIM techniques, as well as advantages, limitations, maturity in the offshore industry, probability of detection (POD) and monitoring capabilities of these techniques, have been reviewed in this thesis study. Chapter 4 will discuss some critical items in oil & gas platforms which are difficult to detect. Life extension of offshore structures can be obtained to monitor these critical items by using proper SIM techniques.

Chapter 1. Theoretical background

The subchapters below cover an overview of SI monitoring, applicable codes and standards, SI management and phases, design of fixed and floated offshore structures. It is an essential chapter that must be comprehended to understand the next chapters in this thesis.

1.1 Literature survey of SIM in general

With the ageing of oil & gas platforms, Structural integrity monitoring is going essential around the world. These ageing platforms are subjected to numerous forces during their operational life. These forces interact with foundations and topsides installation, jacking operations and results fatigue and other issues in platforms. Fatigue and other issues will affect offshore platforms in the long run if any SI monitoring is not operated [5]. The question is, how will offshore platforms suffer, and will they be remaining efficient during or even beyond their service lives? The response starts with collecting data with the help of structural integrity monitoring.

SI monitoring techniques provide on-demand and ongoing information for structural integrity to increase the design lives of offshore platforms. SI monitoring uses a variety of sensors to evaluate any dynamic change for the framework of the system that needs to be monitored. Then, the evaluation phase is done with the application of post-measurement or data to evaluate structural integrity.

The aims of the SIM are the followings [6]:

- Identify structural problems that may have an influence on future use.
- Perform a structural assessment against the applicable failure modes.
- Determine the activities to avoid or mitigate potential hazards.
- Summarize the consequences of monitoring performed for structural assessment of offshore platforms.

NDT techniques are part of SI monitoring that is widely used to detect items of structure for a certain period, known as the local damage technique.

1.2 Currently available codes and standards

Table 1 lists the main current standards containing design procedures and assessments that explicitly make reference to SI monitoring.

Table 1: ISO, NORSOK, DNV, API

Standard	Title	CONTEXT
ISO 19902: 2020 [7]	Petroleum and Natural Gas Industries–Fixed Steel Offshore Structures	In-service monitoring and SI management. Design specifications and regulations for fixed offshore platforms.
ISO 19906:2010 [8]	Petroleum and natural gas industries. Arctic offshore facilities	Independent of the type of structure or the type of materials chosen, provide a high level of reliability for offshore platforms both with and without staff.
API [9]	Recommended practice for the SI Management of Fixed Offshore Structures	It can be applied for analyzing joints, the connection which is sensitive to fatigue and cracks.
NORSOK N-001: 2020 [10]	Integrity of Offshore Structures	This standard establishes the main principles for the design of offshore platforms. It can be applied to any offshore structures and their parts, including topside, foundation, underwater construction and subsea installations, as well.
NORSOK N-003: 2017 [11]	Actions and action effects	outlines fundamental concepts and procedures for determining action and effect for structural design.
NORSOK N-004: 2021 [12]	Design of Steel Structures	It establishes design principles and specifications for steel structures, their design and construction. It applies to a variety of offshore steel constructions with a minimum yield strength less than or same to 500 MPa.
NORSOK N-005: 2019 [13]	Condition Monitoring of Load-Bearing Structures	It covers main principles and requirements for safety and costs during offshore platforms' design, operation, and decommissioning. The main purpose of this standard is to get the structural integrity of structures that are under loads.
NORSOK N-006[14]	Assessment of structural integrity for existing offshore loadbearing structures	This standard provides additional guidelines for SI monitoring in-service operations and extension of service lives of offshore structures.
ISO 16587[15]	Applicable to stationary structures	This standard covers the assessment of offshore structures' conditions such as measuring of data acquisition parameters and eligible performance boundaries for universal databases and globally accepted guidelines.
DNVGL RP-C203: 2019 [16]	Fatigue Design of Offshore Steel Structures	Principles and recommendations connected with the design of fatigue according to failure analysis and fatigue testing.

API RP-2SIM: 2021 [18]	Strengthening modification and repair by API RP-2SIM "Structural integrity management of fixed offshore structures"	A comprehensive SI management process is presented in this standard. It includes data and suggested requirements for the US areas such as GoM and West Coast.

API (American Petroleum Institute) has initiated the development of the petroleum, natural gas, and petrochemical technology and operational procedures in the United States locations for almost 90 years. As of the present, API has nearly 700 standards and guidelines. Although API primarily focuses on the United States, they have extended their activity and are now known globally with their standards and guidelines.

NORSOK standards play a crucial role in the design and investigation of steel structures. All NORSOK standards contain detailed information about recommendations, guidelines, principles, figures, tables and frames. This improves human safety, lowers operational costs and reduce pollution in the atmosphere. These standards aim to provide functional, structural integrity from manufacturing through final disposal of offshore jacket structures in design, installations and evaluation. In this thesis, the NORSOK standards are applied as an addition to the ISO standards and DNV GL's suggested practice.

The ISO 19900 family of standards is concerned with the design, manufacturing, installation, integrity, and appraisal of offshore structures. It was in the early 1990s that leading companies came up with a long-term plan to create and manage a number of international standards that would eventually replace a rapid rise in local and regional standards.

1.3 Structural Integrity Management phases

There are too many cases of early failures in offshore structures that cause serious results. For that reason, development in structural integrity management has exploded. This is mainly achieved for facilities through SI Management, which also defines the arrangements for reaching structural integrity through the periodic interval and guaranteeing the safety and health of humans, as well as managing the integrity of a structure, floating structures, subsea systems in-place and will carry out during the lifetime of structures while needed [17]. The procedure of understanding the ageing, impacts of damage, variations in loading, and accidental overloading is characterized in structural integrity management. SI Management also provides the basis for understanding, analyzing, maintaining, and repairing offshore platforms. There are 5 phases of Structural Integrity Management which are operated through the service lives of platforms [18].

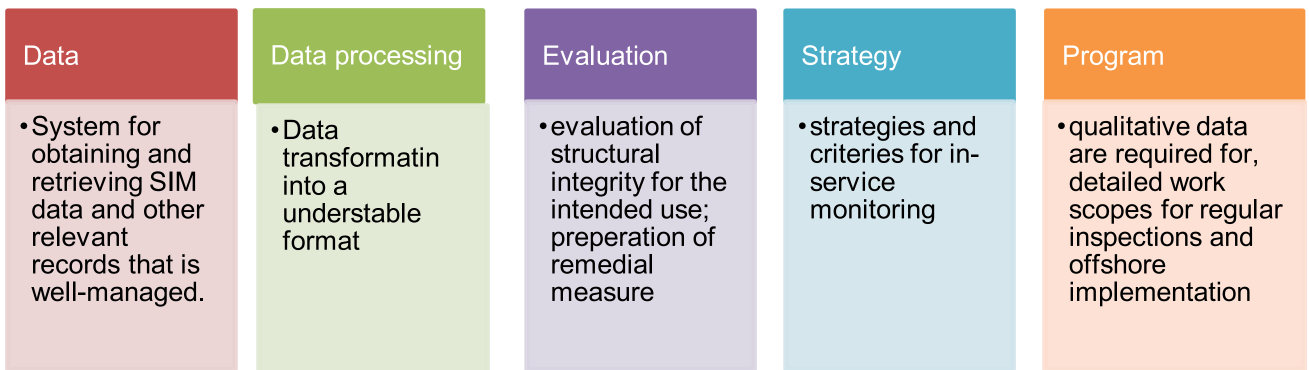

Figure 1:SI management phases [18].

1. Data collection

Data collection is the phase of a compressive data management system to clarify platforms' characteristics and conditions to provide a real-time monitoring evaluation process. In this stage, current operational/environmental loads should be taken into account in relation to the collected data from the sensors to ensure their reliability. In addition, collected data should be filtered from environmental noises to obtain real data.

Data collection aims to provide real-time monitoring. Therefore, it is essential to enhance the effectiveness and robustness of facilities. Relevant following data is required to obtain SI monitoring of offshore structures [19]:

- Fabrication process.
- Installation - including variations from standards.
- History of facilities.
- Environmental factors and any deviation with respect to the design data.
- Fatigue impact on the offshore structure.
- Corrosion impact on offshore structure.

2. Data processing phase:

This phase includes a large amount of data, analyzing and selecting the most significant data and processing them to determine indicators for the damage parameters and convert them into an understandable way. So after that, the evaluation of data could be managed. It is essential to settle which type of method should be used to identify damage. Local and global structural integrity monitoring techniques could record all the failure mechanisms and achieve redundancy in the monitoring system.

FFT (Fast Fourier Transform) is widely used to achieve structural Integrity in offshore structures and other engineering applications. Amplitude data in time break down into frequency as illustrated in the frequency-amplitude plot. (1.21) and (1.22) identify the integrals that are used to transform data from time to frequency domain and vice versa.

$$F(v) = \int_{-\infty}^{\infty} f(t)e^{-2\pi ivt}dt \qquad (1.21)$$

Inverse FT:

$$f(t) = \int_{-\infty}^{\infty} F(v)e^{2\pi ivt}dv \qquad (1.22)$$

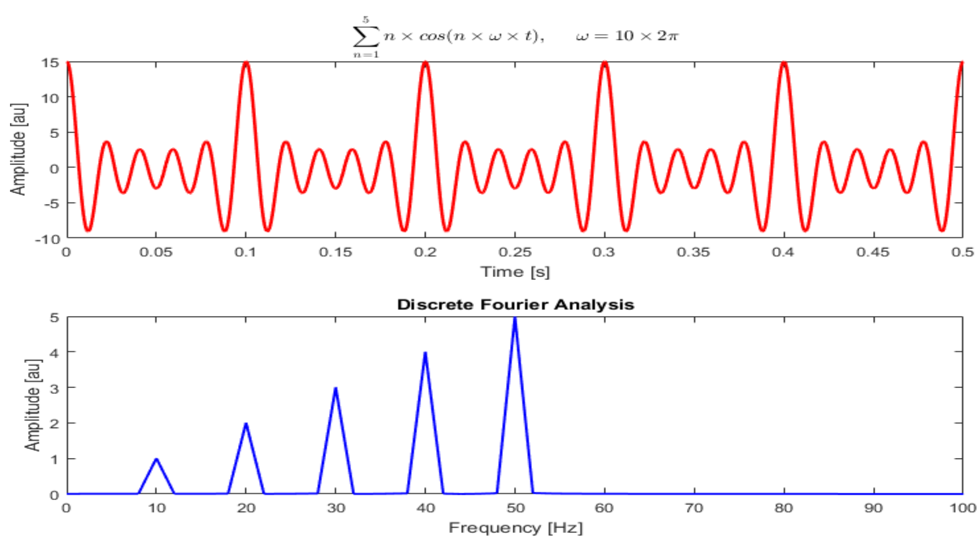

Figure 2: FFT Transform [20]

3. Evaluation phase

Evaluation is an ongoing procedure in the lifetime of offshore platforms. Evaluation is carried out by collecting data. Evaluation is according to damage data that has been processed, passed from filtration and available for evaluation [21]. In this phase, the operator has to define:

1. Detecting the presence of crack initiating, crack growth, crack, corrosion. Etc.
2. Define the presence, location of crack considering the background noises.
3. Define the remaining life of structures' parts.
4. Taking corrective actions and making the decision.

4. Strategy

Inspection and mitigation methods are defined for a platform or group of platforms in the SI management strategy. It may also describe any potential prospects and/or limitations for the facilities. In addition, strategies are defined for any mitigation and control measurements that might be implemented in order to obtain structural integrity. The description of equipment, recording of any discontinuities, personals' responsibilities and duties, inspection criteria and corresponding programs should all be included in the strategy [22].

5. Program

During the operation of structures, data is obtained through periodic inspections as a consequence of unforeseen events, intended adjustments, and upgrades to the platform. Those data are subjected to competent engineering analyses, which determine whether or not they influence the current SI management strategy in offshore structures. If required, the program is adjusted in compliance with the shift in strategy, which could imply, e.g., the inspection is becoming more comprehensive. It results in passing from visual testing to non-destructive techniques, or vice versa [22].

1.4 Recalls on structural design of offshore structure

The petroleum industry has developed numerous novel structures to overcome deep-water problems. Offshore platforms can be divided into mobile offshore platforms that can be moved from one location to another and stationary offshore platforms (fixed). Jackets, jack-ups, and compliance towers are examples of fixed

structures. At the same time, semi-submersibles platforms, floating production storage and offloading units (FPSOs), and tension leg platforms are examples of mobile offshore platforms. The selection of a concept is influenced by several parameters, including the size of the reservoir, the depth of the water, and the type of well. The fundamental advantage of fixed offshore platforms is their stability and reliability. Because they are anchored to the seafloor, they can only move a little distance due to the impact of wind, current, and wave forces. These platforms, on the other hand, cannot be applied in excessively deep water. Fixed structures are structures that are permanently placed at the production site (except the jack-up). It means that there are some points on offshore jacket platforms where manual inspection cannot be operated after installation. Fixed structures are permanently installed at the production location (except the jack-up). In contrast, floating structures can be transferred to onshore sites for the maintenance process [23].
For that reason, chapter 3 will focus mainly on structural integrity monitoring of discontinues such as fatigue, cracks, corrosion, member severance in jacket platforms, and monitoring of floating structures' position such as semi-submersible and FSPO. In the following sub-chapters, a short description of the design of Jacket structures, semi-submersible and FSPO, are discussed because they are a case of interest for this thesis work.

1.4.1. Design of jacket structures

Since the engineering of oil and gas production, jacket platforms have been used in the petroleum industry. These platforms are formed of steel or concrete, and steel is mainly used for jacket structures. Steel fixed platforms are made up of 4-8 legs anchored straight to the seabed with piles to provide stability against environmental and other loads. The piles are so essential for the safety of construction. The steel jacket structure also provides support for the topside facilities, including drilling rigs, living quarters, production units. Steel jacket platforms are formed connected tubular members for three-dimensional space. (figure 3). These platforms are mainly used in shallow water up to 500-600 ft. The jacket legs are usually manufactured onshore and then carried out to their final location using installation vessels. Then later, crane ships are used for the installation of topside on the jacket legs [24].

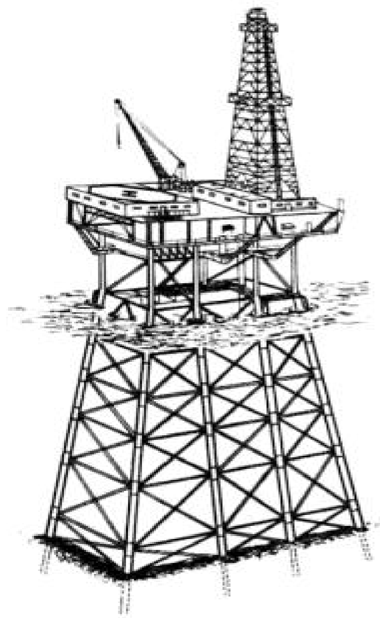

Figure 3: Offshore jacket platform [24]

The design of a Jacket platform is governed by the various limit states given in Table 2. The four limit states which are critical to look for in order to assure comprehensive structural integrity are as follows: [25].

Limit state	Definition
FLS	Potential failure due to cyclic loading
ULS	Ultimate resistance to carry excessive loads
ALS	Failure according to accidental hazard
SLS	This value corresponds to the criteria for use or durability.

Table 2: Limit states for offshore jacket structures [25]

SI monitoring is associated with the examination of structural integrity as well as the remaining prediction lifetime. Therefore, ALS and SLS are not considered applicable for structural integrity. ALS-related damage is those that have no significant impact on the structural integrity of offshore structures, while SLS-related damage is difficult to estimate and control. However, evaluation of ULS, FLS are important for maintaining structural integrity in the design of platforms.

Tubular members

The majority of connections between steel jacket members are provided by welded connections. For that reason, discontinuities such as fatigue, crack, corrosion occur in these tubular members. Tubular members are considered primary load-bearing members in jacket structures [26].

The bracing system is made up mostly vertical, diagonal and horizontal tubular connections that are attached to jacket legs to transfer seismic activity and environmental load on the structure to piles [27]. Figure 4 illustrate the various type of jacket designs such as K-braces, V-braces, X-brace [28].

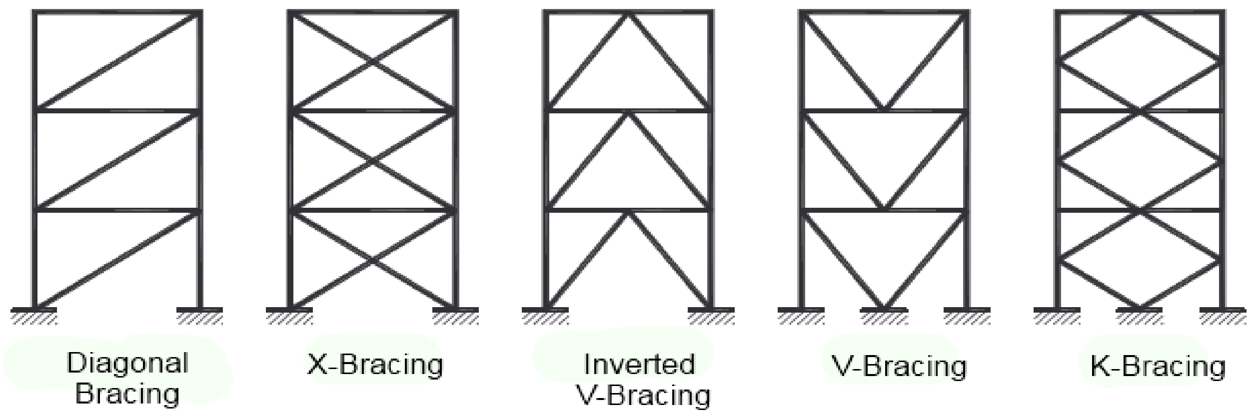

Figure 4 : Bracing geometry for jacket structure [28]

The various structure systems play a key role in distributing the axial force in a variety of ways. (ISO-19902,2007). The advantage of the K brace is that only a few members are intersecting at joints. Welding and installation costs can be lowered in this type of brace. However, the main principle drawback is low redundancy compared to X-bracing. In addition, X-bracing and also horizontal bracing can sustain more lateral load than K-bracing [27].

Most of the failure in tubular members occur due to buckling, which is dependent on extreme loads. Buckling can be characterized as a sudden change in failure which results from the instability of tubular members. It occurs mainly at stress levels that are less than the USL of the material [29]. Buckling can be defined into two categories: Local and Global Buckling. When members with a high d/t ratio, such as thin-walled cylinders, collapse due to crushing or yielding, this is referred to as local buckling. When members with a low d/t ratio, such as thick-walled cylinders, damage due to buckling, this is referred to as global buckling.

1.4.2. Semi-submersible platforms

In offshore installations, the semi-submersible platform is a multi-functional submerged vessel utilized for various tasks such as offshore drilling rigs, oil production platforms, safety vessels and heavy lift cranes. Semi-submersible platforms are floating structures that consist of multiple legs and decks. The legs are attached at the bottom of the sea with horizontal buoyant elements known as pontoons. Pontoons give stability and buoyancy for the ballast performance and waterproofing properties. Semi-submersible platforms are towered in a location where pontoons can then be flooded, and the deck can then partially have submerged [24]. Figure 5 shows semi-submersible platforms with two pontoons and four vertical supply columns. It provides a connection of pontoons to the deck. Depending on the situation, this platform can be transferred to chosen position by using mooring anchors, chain [30].

Figure 5: semi-submersible platform [30]

Mooring lines are needed to maintain the stability of platforms. The Mooring system should meet the accuracy requirement with a max error of 1% of water to get an assigned location. It is the main factor to maintain the platform in a place [30].

1.4.3. Floating Production Storage and Offloading Units(FSPO)

For deep production, FPSOs are an effective option. It is possible to rotate the vessel or keep the vessel's desired heading by mooring system, which protects the platform from different environmental loads [31]. Furthermore, they are a more cost-effective choice for more marginal areas, as the vessel may be transferred to a new location for further use and then moved again after that area has been drained and the new location has been established. FPSOs are also considered an excellent choice for construction in areas where there are no existing pipelines or infrastructure for bringing supply onshore [32].

Risers provide the connection between subsea fields, production and drilling facilities. Risers can be rigid or flexible, which transport produced oil and gas from wellhead to floating unit while also production materials, such as injection fluids, control fluids and gas lift as illustrated in figure 6 [33].

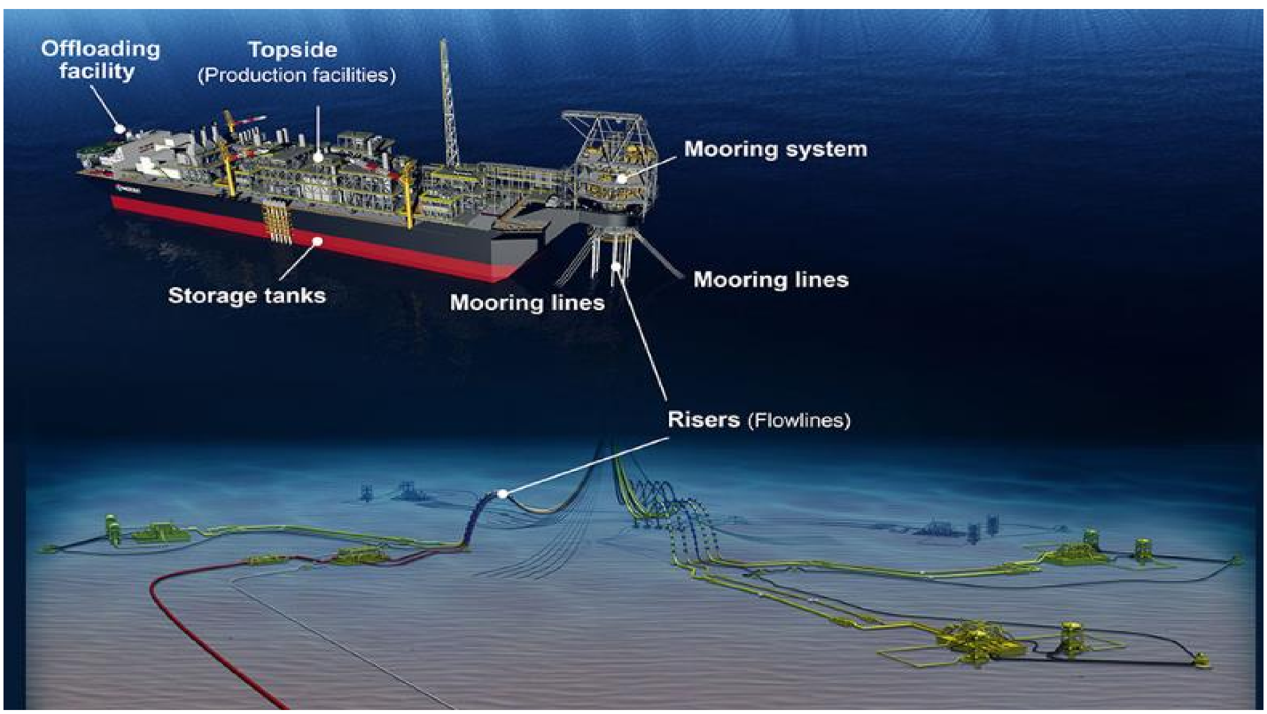

Figure 6: FSPO [33]

Chapter 2. Common loads, failures, and damage on jacket structures

This chapter will provide details on the most prevalent failures in offshore jacket structures. This includes damage parameters as well as parts or spots that are most influenced by these failures in these structures.

2.1 LOADS

The offshore platforms have subjected a variety of loads or stresses during their service lives, including gravity, hydrostatic, earthquake and mainly environmental loads (wind, currents and waves). Figure 7 depicts overview loads that have an impact on fixed offshore platforms [34].

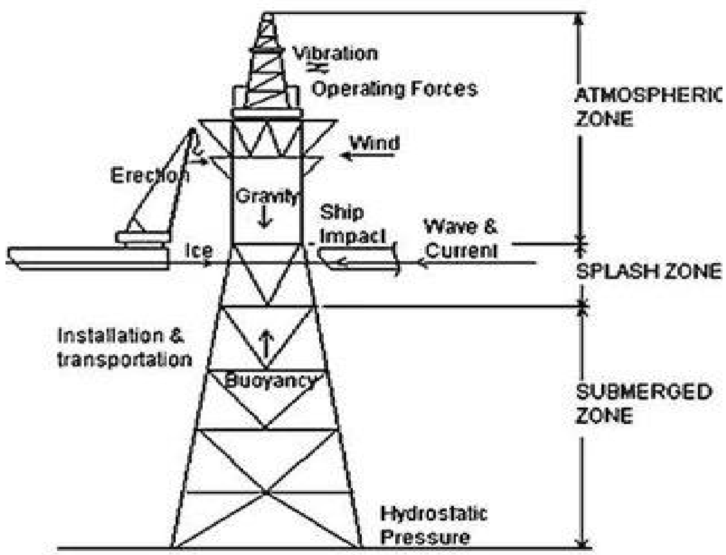

Figure 7: Overview of loads on fixed offshore platform [34]

The loads are primarily taken into account when designing offshore installations. Gravity, environmental, accidental and deformations loads are four types of loads that can be classified.

2.1.1. Gravity loads

Gravity loads can be characterized as dead and live loads. Different kinds of weights such as the weight of topside structures, steel jackets and production facilities are potential dead loads acting on offshore platforms. Live loads exist on the offshore platforms for a limited time, for example, the weight of facilities temporarily through maintenance, helicopter landings and the tensile force of loads, impact of mooring lines, and loads caused by platform activities. The gravity load typically accounts for 60 to 70% of the total acting loads [34].

2.1.2. Environmental loads

Figure 8 shows the environmental loads induced on the platforms by wind, current and waves. 90% of the overall environmental loads are subjected to current and wave loads and with the remaining 10% due to wind. On the offshore platforms, environmental loads account for 30 to 40 % of total imposed loads [34]. The American Petroleum Institute (API) provides recommendations and standards for the calculation of wave, current and wind loads [9].

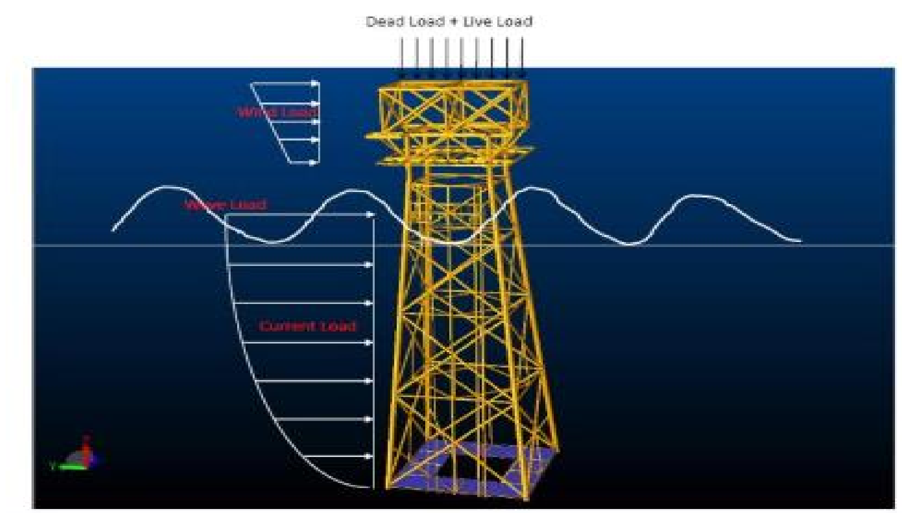

Figure 8: Environmental loads [34]

For advancing the structural integrity of offshore structures, ice, temperature loads, and marine growth should all be considered.

2.1.3. Accidental loads

Accidental loads can happen as a consequence of an accident or other unforeseen circumstances, for example, collisions with vessels, fires, explosions, dropped objects, and unintentional flooding of buoyancy tanks [34].

2.1.4. Deformation loads

It involves inertia and deformation loads that happen during the manufacturing, displacement and rotation of module supports [34].

2.2 Damage parameters and failure modes

In 1994, The Marine Technology Directorate(MTD) released a report titled "Review of repair to offshore structure and pipelines" that detailed various damage causes [35]. Offshore structures made of steel and concrete are included in this report. In steel structures, 158 separate damage cases were discovered, while the concrete structure had 14 different damage. According to the report, 39 of the 158 separate damage cases were reported as fatigue damage. Furthermore, the second most common cases were recoded as vessel impact. According to the MTD report, Table 3 displays these causes of damage and the number of incidents [35].

Cause of damage	Number of incidents
Fatigue	39
Vessel impact	36
Dropped object	14
Fabrication fault	12
Installation fault	12
Corrosion	10
Design fault	9
Operating fault	4
Design upgrade	11
Others	8
unknown	3

Table 3: causes of damage in steel structure (MTD 1994) [35]

2.2.1 Fatigue

Fatigue, as indicated in the table above, is a major failure of the material. It is caused by the loads that impact the structure continuously. The crack starts to grow in the material when the loads are affected again or even after the withdrawal of loads. Fatigue happens in parts of the structure where cyclic loads are acting

[36]. Fatigue damage manifests itself in the form of crack, which starts with initiation, progresses to a through-thickness stage and results in member severance. It mainly occurs at welded connection [3]. Fatigue can be classified into three parts:

- **Crack initiation**: Fatigue is the crack initiation and growth process that is impacted by microstructural characteristics, localized cyclic deformation, loads and stresses. In this stage of crack, the material begins to develop microscopic plastic degradation under excessive cyclic loads. As cyclic loading continues, the material accumulates more flaws that cause it to pass the next stage. The initiation stage is normally visible on the material's surface [36].
- **Crack growth**: It starts when the crack propagates outside the first grain and hits surrounding grains. Additional cyclic loads and energy are important for the transition from first grain to second. In this case, the crack starts to propagate in a new direction and follows the crystal orientation of the second grain [37]. The next equation is used to evaluate crack growth [38].

$$\frac{da}{dN} = C\Delta K^{m} \qquad (2.1)$$

Where $\frac{da}{dN}$ is crack growth rate, ΔK is stress intensity factor which is defined following formula:

$$\Delta K = K_{max} - K_{\min} \qquad (2.2)$$

C is the Paris law coefficient, (mm/cycle)/ (($MPa.$ $(mm)^{0.5}$) ^{n}),

n is the Paris law exponent.

K_{max} is maximum, and K_{min} is minimum stress intensity factors corresponding to the maximal and minimal load in a cycle, respectively. C and m are constant values and dependent on the microstructure properties, fatigue frequency, stress, weather condition, loading, stress state and temperature. It is possible to compare three different regimes of crack growth from the diagram in Figure 9 [39].

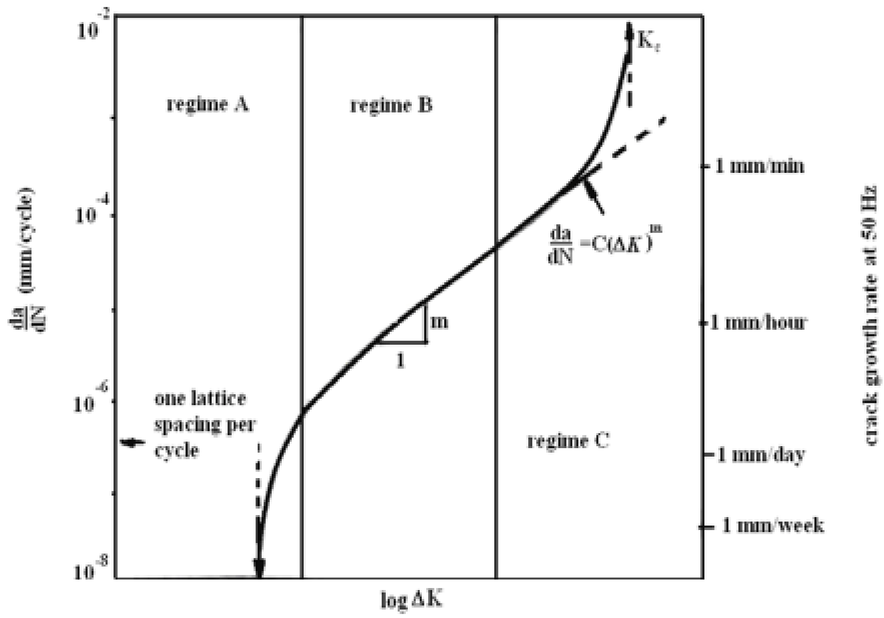

Figure 9 : Different regimes of stable fatigue crack propagation [39]

- The average crack growth increase in regime A is less than one lattice spacing per cycle which is linked to a threshold stress intensity factor range, ΔKth. Under this threshold, crack does not exist or grow extremely slow, followed by a rapid increase in da/dN as K increases.
- According to Paris, which denotes the linear relationship between log(da/dN) and log(K) in regime B, it is only applicable to the part of the growth curve where fatigue grows at a stable rate.
- In the C regime, the value of ΔK is very high and ends up at the value of critical stress intensity (Kc). For that reason, crack growth occurs fast and reaches the final fracture.

In the final collapse (crack): linear elastic fracture mechanics (LEFM) depend on the examination of stress-field equations, which indicate the stress field in the part of a crack that may be characterized by a stress intensity factor (ΔK). The following equation is for predicting crack propagation:

$$\frac{da}{dN} = f\left(\Delta K_{,}\ R_{,}\ H\right) \qquad (2.3)$$

Where ΔK is the stress intensity factor ranges $MP_a*(mm)^{0.5}$

N is the number of loading cycles,

da/dN is the crack growth per cycle, mm/cycle.

a is the crack length in mm, H is the history term,

$R = Kmin/Kmax$

Fatigue depends on characteristics of material, including, yield strength, and Young's modulus.

2.3. Fatigue analysis

Different approaches for measuring and calculating the fatigue strength of materials have been developed over the years. The following is a short comparison of various approaches.

Hot Spot Stress (HSS) Method.

In circumstances where the nominal stress is tough to predict due to geometry, loads, or other factors, the Hot spot stress approach was created to precisely assess the effect of fatigue on welded connections. The following equation describes the linear between nominal stress and Hot spot stress [40].

$$\sigma_{\text{hotspot}} = SCF * \sigma_{\text{nominal}} \qquad (2.4)$$

SCF is stress concentration determinant, σ_{hotspot} is hot spot stress, σ_{nominal} is nominal stress.

Generally, hot spots can be distinguished into two types [41]:

1. The weld toe is placed on a plate surface.
2. The weld toe is placed on a plate edge.

The negative side of this approach is that it can only be used for weld toes when the cracks begin on the material's surface. Furthermore, mesh sensitivity of the hot spot stress is a problem with this method. According to DNVGL-RP-C203, measuring the highest SCF allows for the identification of the essential areas on the jacket structure where the crack is most likely to start. In this part of the structure, proper NDT sensors can be mounted to detect any discontinuities at an early stage.

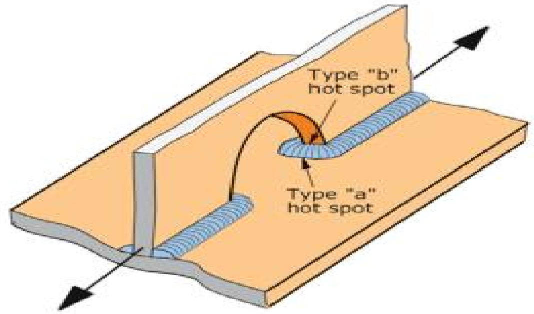

Figure 10: Examples of two types of hot spots in the weld [41]

❖ S-N curves method for fatigue analysis.

Fatigue analysis utilizing the S-N curves is obtained from the Miner-Palmgren method to determine the fatigue life. It is represented as the relation between the expected number of cyclic stress and the number of stress which cause failure. The fatigue damage can be computed using Miner's formula and is described in the subsequent equation [42]: $D = \Sigma_{n=1}^{k} \frac{n_i}{N_1}$ (2.5)

D= the damage accumulation,

n= the expected number of cycles,

N=the total number of cycles required to cause fatigue failure.

S-N curves are used to describe the stress-lifetime relationship, with S being the stress range (specified as in this thesis) and N being the number of cycles to failure (Fig.11). Consequently, the less applied cyclic stress range is related to the longer the fatigue life in offshore structures [43].

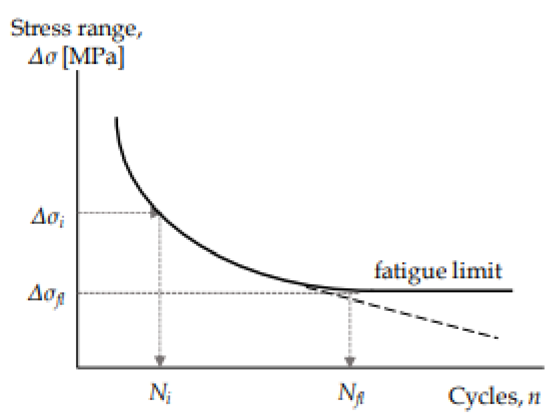

Figure 11: S-N curve [43]

2.3 Corrosion

Corrosion is another significant detail to consider when designing components for use in severe environments. Corrosion is the physical decomposition and destruction of a material (typically metals) caused by chemical or electrochemical processes in an environment that promotes these processes. The corrosion causes structural integrity to erode. Due to the appearance of seawater and oxygen in offshore platforms, the most aggressive and ideal location for corrosion will be above or below sea level. This area is known as the splash zone, and it is considered a very corrosive zone and needs to be monitored frequently for the structural integrity of platforms. The Corrosion Protection System (CPS) is usually applied to prevent the surface area from corrosion. However, it only lasts 5-15 years on average.

The most frequent types of corrosion are uniform and pitting corrosion (Fig. 12). Because of the consistent impact of corrosion damage on the surface area, these types of corrosion decrease the total member thickness. Pitting corrosion occurs in the splash zone where CPS has low effectiveness. Pitting corrosion can also begin long before the CPS misses its effectiveness [44].

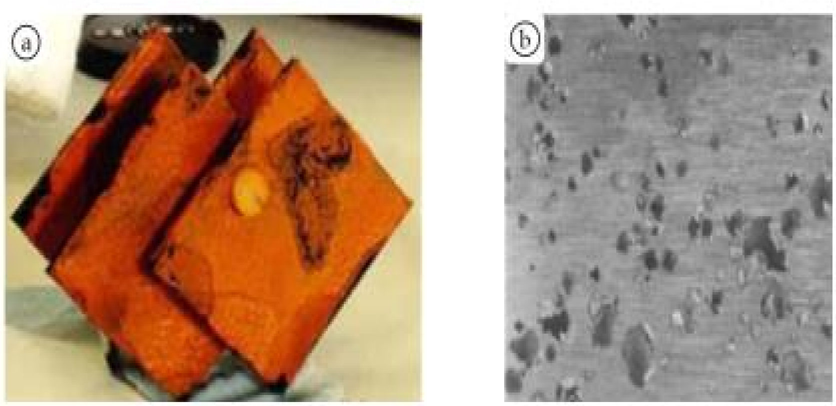

Figure 12: a. uniform corrosion b. pitting corrosion [44]

Offshore constructions are subjected to cyclic loads (wind, current, and wave loads) as well as corrosive conditions. The corrosion rate of steel in this hostile environment might range between 0.1 and 0.7 mm/year in a non-protected area, depending on the type of steel used [45].

Chapter 3. Review of SIM techniques

The chapter discusses the SI monitoring approaches that are currently available, as well as the global and local damage methods (especially common non-destructive testing techniques) for offshore structures due to international guidelines and standards. The criteria for selecting the most applicable method for each type of failure and cost-effectiveness are discussed. The characteristics of these techniques, as well as their monitoring capabilities, advantages, limitations, and probability of detection (POD), are illustrated in this chapter.

3.1 Overview and inspection requirements

Structural Integrity Monitoring (SIM) is the process of analyzing the structures with multiple sensors. Through the operational process, sensors are placed to detect any structural damage and failures that may have occurred. Techniques for monitoring structural integrity can be divided into local damage monitoring techniques and global damage monitoring techniques [46].

3.1.1 Global Damage Monitoring Technique

This technique is used to examine the structural integrity of the whole structure, as well as its degradation and ageing and can both identify the existence of the damage and the location of that damage. Global damage technique is used to monitor the entire structure depending on changes in the global properties of the offshore structure (Mass, Damping, Stiffness), while Local technique can only be used to detect accurate damage localization or points of damage [47].

The vibration-based monitoring technique is a global damage technique and is widely used in the offshore industry. It usually entails the use of accelerometers to measure the structure's vibration at specific points or places, followed by the calculation of the structure's modal characteristics according to vibration data [48]. The position of floating structures and air gap can be detected by using global methods.

3.2.2. Local Damage Technique

The need for detailed damage identification is the key driver for the use of local techniques in structural integrity monitoring. As the number of ageing structures increased, the requirement for monitoring techniques that may find unseen defects has increased, resulting in the development of non-destructive testing (NDT) using a variety of sensors. NDT is a local damage technique that provides Real-time Monitoring through service lives of offshore platforms. These techniques can be characterized as remote sensing, cost-effective operation, process safety, and high reliability. It can only detect limited areas where sensors are mounted. With these sensors, the spots near these sensors could be monitored. The main advantage of this damage technique is to detect abnormalities without causing damage to the structure itself. [49]. There are various types of non-destructive testing (NDT) techniques that can perform depending on the geometry, properties of the material, failure mechanisms of the structure, location and size of the flaws, and historical data [50].

Local Damage Technique compared to Global damage technique is considered a time-consuming and expensive technique. But, it is extensively employed in the petroleum industry due to its high accuracy, efficiency for damage detection. Table 4 shows various characteristics of local and global monitoring techniques.

Table 4 : features and difference of Local and Global damage monitoring techniques

Features	**Local Monitoring Technique**	**Global Monitoring technique**
Common techniques	Non Destructive Techniques	Vibration based technique (Structural Health Monitoring)
Objectives	Accurate damage localization	Just flaw existence
Duration of Monitoring	Periodic	Continue
Testing duration	More time needed	Less time needed
Manned	Generally, yes	No
Cost of techniques	On a long-term, it is very expensive.	Expenses are higher during the initial period

In the following pages summaries information about available Structural Integrity Monitoring techniques that are used in oil & gas platforms last 10 years.

3.2 Common Non-Destructive Techniques

3.2.1 Visual Inspection

Description of method:

Visual testing is the most commonly utilized non-destructive technique (NDT) because It applied even when other SI techniques are performed. For example, after a component has been magnetized, the experienced operator undertakes a visual inspection to check for magnetic particle testing (MPI) signs.

Visual Inspection is performed mainly by applying an ROV or a camera system that are effective to detect significant discontinuities. Detailed visual Inspection is another approach for finding any defects. However, this technique requires minimal cleaning for marine growth to check cathodic protection conditions, and it is also being used to detect damage in weld connection and corrosion. Visual Inspection is mainly performed for Inspection before NDT is applied. Nowadays, Different types of devices such as magnifying glass, borescopes, UV lights are used in the inspection process instead of performing visual Inspection with the naked eye. Rigid borescopes are a useful device for monitoring the inside of tubes or pipelines, especially in difficult-to-reach areas, as shown in Figure 13. Borescopes are available with a variety of angles of view, including 0° straight, 45° fore-oblique, 90° lateral, and 110° retro. Most of them have a focus control and magnification of up to 20×. Borescopes with a diameter of 1.75 mm have been developed to access very small damages [51].

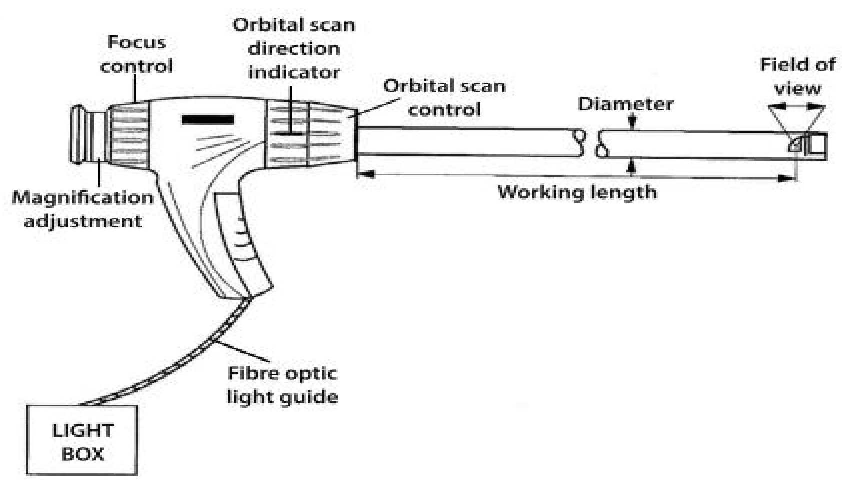

Figure 13 :A typical 0° direct view borescope [51]

An ROV, or remotely operated vehicle, is for investigating underwater and is widely applied for visual inspection. ROVs are automated, innovative working underwater vehicles that can be used to investigate seafloor while being managed from the water's surface by an operator.

They are piloted by a microprocessor-based control system that interacts with them over electrical fiber-optic umbilical. An underwater ROV is a well-organized technology, including a lighting system and a video camera, to record a picture of the seafloor and damage in the structure. ROV is included with equipment and devices such as a manipulator to check water temperature and also collect samples. ROVs are used to carry out a range of operations in offshore oilfields in water depths such as drilling operations, subsea facilities installation, an inspection of pipelines and subsea production facilities. Here is an illustration of a remotely operated vehicle (ROV) system, which is usually applied in subsea technology [52] [53].

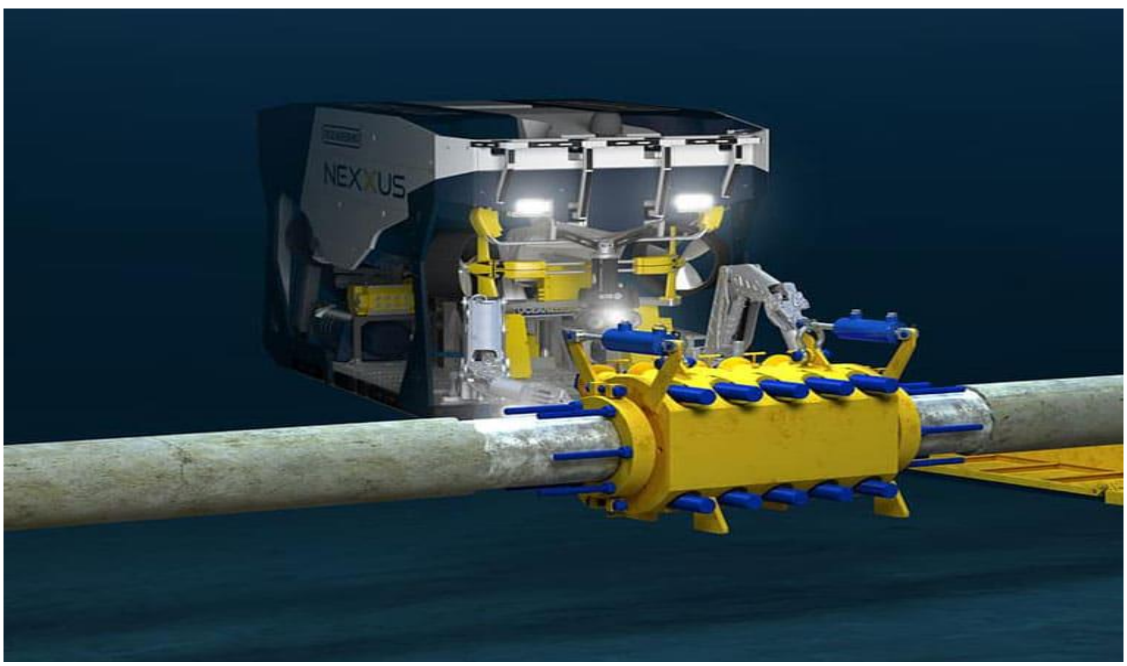

Figure 14: ROV system [53]

Monitoring capability: defects such as visible cracks, dents, gouges, abrasion, erosion, surface-breaking discontinuities and surface corrosion.

Advantages of visual Inspection [51]:

- ❖ Immediate results can be obtained.
- ❖ It enables discontinuities to be observed rather than being reduced to a blip on the screen.
- ❖ Several distinct types of surface-breaking discontinuities that can be discovered.
- ❖ Relatively cheap procedure.

Limitations [51]: Only available for detecting surface flaws.

Maturity in the offshore industry:

It is possible to observe cathodic protection conditions on the surface of structures and large abnormalities by visual inspection using ROVs.

Requirements: Advanced technology and highly skilled operators are needed.

Probability of detection (POD):

While GVI (general visual inspection) and close visual inspection (CVI) are applied to detect visible cracks and the state of the structure, however, it can be used to detect embedded cracks. Visual inspection depends on where fatigue propagates depends and the type of the fatigue crack. It will be more tough to estimate the level of fatigue if fatigue propagate in welded connection compared to plate thickness. [54]. The following calculation is used to compute the PoD for visual testing [54]:

$$PoD(ax) = 1 - \left(\frac{1}{1+\left(\frac{x}{x_0}\right)^b}\right) \qquad (3.1)$$

x - Crack length in mm

b, x_0 for visual inspection in various condition is shown table 5.

Table 5 : b, x_0 values for inspection PoD [54]

Description	B	x_0
Easy access	**1.078**	**15.77**
Moderate access	**0.953**	**37.14**
Hard access	**1.079**	**83.02**

In comparison to other NDT techniques, visual inspection shows less reliability or PoD when crack size increase, as illustrated in Figure 15. It is clearly seen, Visual inspection can only be applied for visible cracks, not deeper cracks.

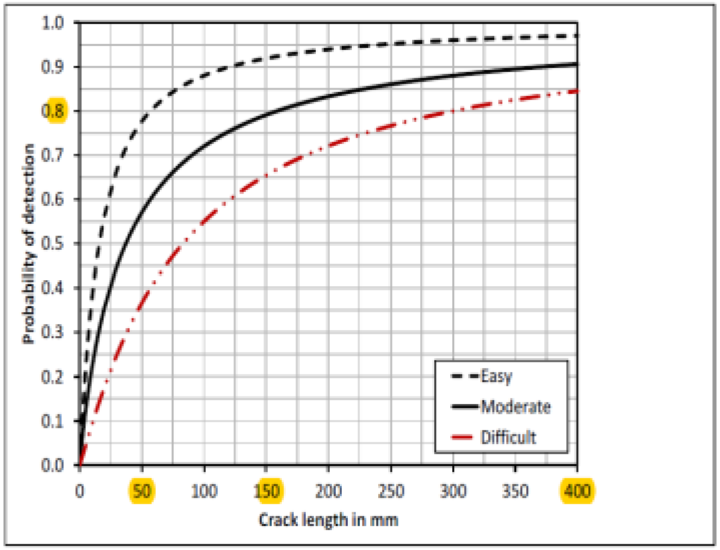

Figure 15: PoD for Visual testing [54]

3.2.2 Ultrasonic testing

It works by transmitting ultrasonic signals through the structural material, then receiving the reflected (pulse-echo) or transmitted waves to the same or another transducer. The receiver/pulser, transducer, and display device are components of a conventional pulse-echo UT. A pulser/receiver is an electrical device that sends high-voltage electrical pulses below the lead to the transducer, also known as the initial pulse. The transducer is attached to a component, and the couplant secures that ultrasonic signals are transferred efficiently. Generating ultrasonic beams with piezoelectric probes triggered by an electric pulse causes the piezoelectric element to vibrate and generate mechanical waves with a large frequency range, typically between 1 MHz and 10 MHz [56].

The sound travels as a sequence of short-duration waves through the component. If there is a discontinuity in the wave path, such as a crack, some part of the energy is reflected from the surface of that discontinuity. The transducer converts the reflected wave signal into an electrical signal, then seen on the screen. Travel time can be estimated by knowing wave velocity, signal travelling distance. Information regarding the reflector's location, size, direction, and other characteristics can be obtained from the signal. [50] [53].

This technique is utilized to monitor corrosion by measuring the specimen's wall thickness and identifying the size of fatigue cracks. It also covers the whole thickness of a specimen during the inspection.

Figure 16 represents a working principle of pulser/receiver UT (Structural Diagnostics Inc.), in which the exciter and receiver of UV signals are located across the plate cross-sectional area.

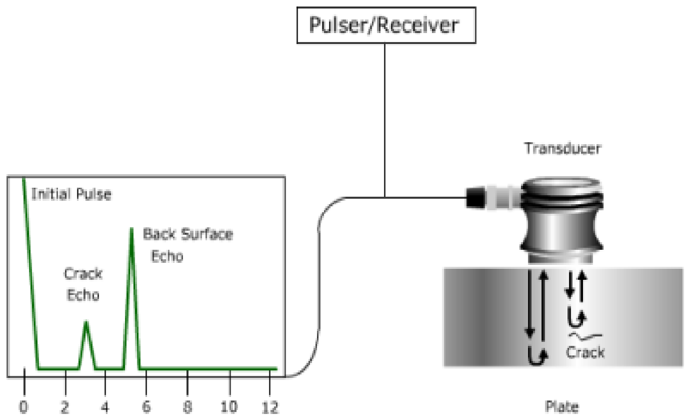

Figure 16: Ultrasonic non-destructive technique [56]

There are 3 types of ultrasonic testing techniques that are largely used in offshore industry:

Typical pulse- echo ultrasonic testing: explained above

Long Range UT: Long-range ultrasonic testing (LRT) is a unique non-destructive method developed to evaluate significant amounts of material from a single spot. This method varies from standard ultrasonic testing methods. Here, the use of a couplant is not required between the surface and transducer. For those factors, Long-range ultrasonic testing has a high capacity to inspect a large volume of pipelines from a single transducer position and is considered the fastest inspection tool for detecting discontinuities such as fatigue cracks, corrosion, coating removal, and corrosion, as presented in Figure 17 [55].

Angled UT: flaws such as through-thickness cracks, embedded cracks and severance can be monitored using this technique [3].

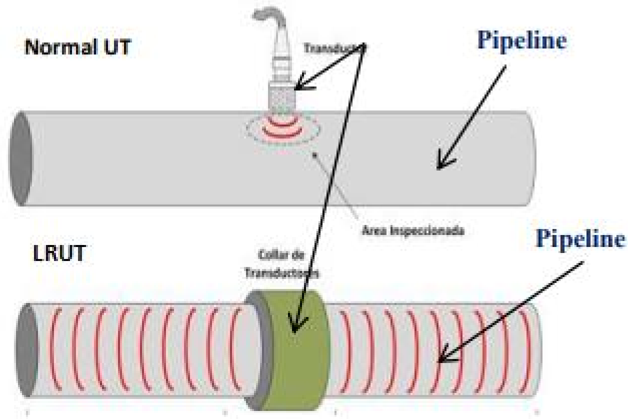

Figure 17:UT and LRUT [53]

Monitoring capability:

Wall thickness, fatigue crack, through-thickness cracks, far surface and embedded cracks, corrosion severance.

Advantages [50]:

- Deep-lying flaws can be detected using this method. Parts ranging in thickness from a few millimeters (for small flaws) to several meters in length can be monitored.
- With the pulse-echo UT technique, only one side of a component needs to be accessed for inspection.
- Permanent records can be achieved.
- It is possible doing an on-site inspection of structures' components where It is difficult to access.
- Defects and properties of the material can be characterized.
- It causes no harmful effects on the environment or humans.

Limitations [50]:

- Ultrasound must be able to pass through the surface to be transmitted.
- Parts with irregular-shapes pieces and rough surfaces harder to monitor.
- The cost of equipment and training is extremely expensive.
- It is possible that linear defects aligned parallel to the sound wave will not be noticed.
- It is necessary to use a coupling in pulse-echo UT in order to transfer the sound wave to the material.

Maturity in the offshore industry: UT is generally used to estimate the thickness of the wall and flaw's location. UT is a quite costly operation. It requires an external exciter to send the high-frequency waves to the structure's parts.

Requirements: Experienced operators, advanced technology and calibration are needed. Couplant is required in most cases.

Probability of detection:

For the POD curve, the same equation will be applicable. Where:

a= Depth of the crack in mm

x_0=0.410, b =0.642.

As seen in Figure 18, UT can detect 4 mm crack size underwater, indicating that this method is much more reliable for detecting fine cracks than the other technique [54].

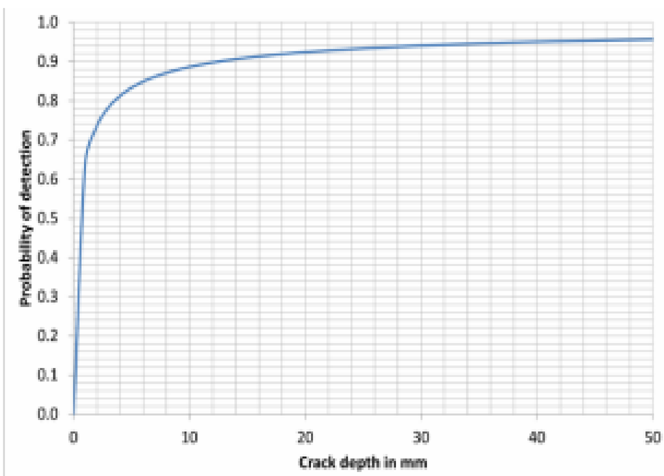

Figure 18 : PoD for ultrasonic testing [54]

3.2.3. Magnetic Particle Inspection

Magnetic particle inspection (MPI) is excessively used as NDT to inspect structures' elements regarding creating a magnetic field. A magnetic field is formed at the element of the material or below the material's surface. It is based on the application of a permanent magnet and an electric current in order to magnetize the material either locally or throughout. Inside the material, a magnetic field is generated, and if there are any discontinuities such as cracks are detected near the surface of the material, this will result in the formation of local magnetic leakage fields. The only requirement for magnetic leakage is that inspected components should be ferromagnetic material. Ferromagnetic material attracts the particles by creating a magnetic field, making the leakage detectable.

To sum up, magnetic particles are placed on the surface of the magnetized component after it has been magnetized. Those magnetized particles will be attracted to the leakage fields and produce a visible sign that the inspector will notice discontinuities. Metals such as iron, nickel, cobalt, or alloys can be examples of these materials. This technique is only working for ferromagnetic materials [56] [57].

Surface and near-surface defects like cracks, fatigue cracks, and weld defects are inspected using this technique. Magnetic particle inspection can be applied in different industries, including steel, automotive, and aerospace. The working principle of MPI is depicted in Figure 19.

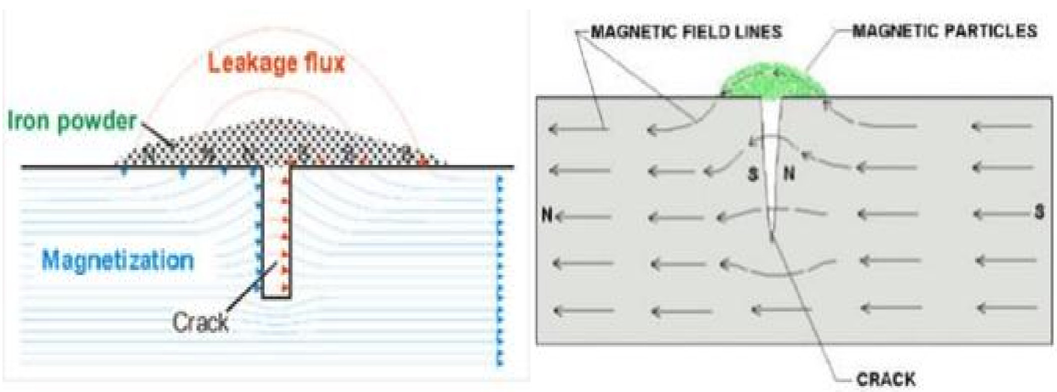

Figure 19: Magnetic particle inspection [56]

Besides visual inspection, MPI has been the most extensively used method for applying underwater structures. It's a highly successful technique for detecting surface-breaking cracks, both underwater and above water. It's considered a time-consuming procedure because it usually requires surface cleaning before use [56].

Monitoring capability: surface breaking cracks, sometimes through-thickness cracks.

Advantages [56]:

- MPI is a sensitive method for detecting microscopic discontinuities, surface and open-surface flaws, and other types of defects.
- Low cost and quick technique.

Limitations [56]**:**

- It can only be applied to ferromagnetic parts.
- Only used to detect defects on the surface or close to the surface.
- After the test, demagnetization is needed.
- It is necessary to have a constant power source for operation.
- Deeply embedded detects cannot be detected.

Maturity in the offshore industry:

MPI is used to find surface discontinuities such as cracks and welds in ferrous materials, as well as discontinuities just below the surface of the material.

Requirements: Minimal preparation for cleaning is required.

Probability of detection:

POD for MPI is represented in the following equation [54]:

$$Pod(a) = 1 - \left(\frac{1}{1+\left(\frac{a}{x_0}\right)^b}\right) \qquad (3.2)$$

a - Crack depth in mm,

x_0 is Distribution Parameter (50% median value for POD),

b is Distribution parameter,

Table 6: b and x_0 values in different condition for MPI [54]

Description	B	x_0
Good working condition above water	1.42	0.4
Normal working condition above water	0.9	0.46
Below water	0.9	1.17

As demonstrated in Figure 20, detecting a crack below water is much more challenging than above the water [54].

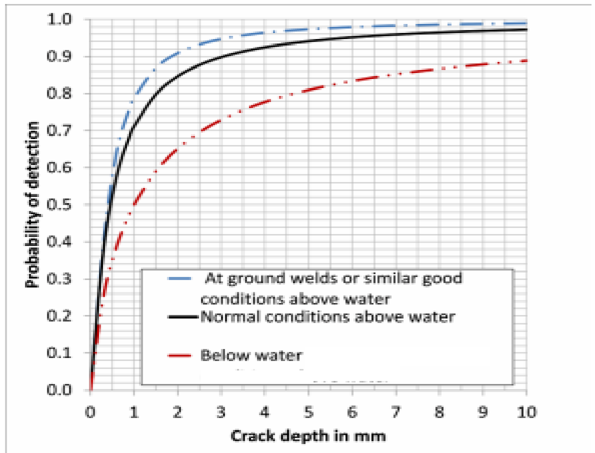

Figure 20 : PoD Curves for MPI [54]

3.2.4. Eddy current Testing

The working principle of this technique is electromagnetism, in which electrical currents are induced in the material being tested, causing the specimen to magnetize. When a coil is approached near a material's surface, the coil's changing magnetic field causes forming of eddy currents. These currents have a tendency to magnetize against the original magnetic field. The presence of induction currents created in the material affects the coil's impedance close to the material. The coil impedance changes when the eddy currents in the material change because of flaws or material abnormalities. Through the wall thickness measurement, this change is measured and shown to indicate the presence of defects and corrosion [59].

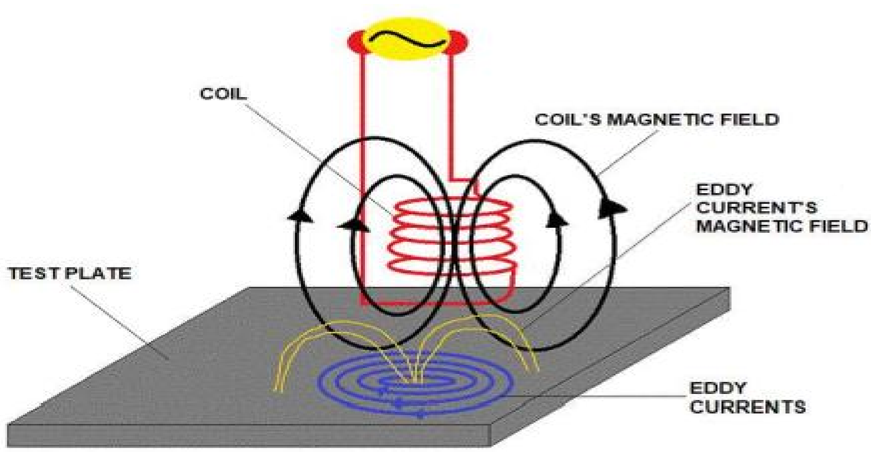

Figure 21: Eddy Current Methods Principal for Non-Destructive Test [58]

Monitoring capability: surface-breaking defects and their size, sometimes through-thickness cracks.

Advantages [57]:

- Small flaws can be found.
- Permanent record capability.
- A coupling is not needed.
- No probe contact required.

Limitations [57]:

- The surface-breaking failures can be found.
- Vibrations and hits will make it more difficult to detect faults.
- Only conductive materials can be inspected.

Maturity in the offshore industry: Surface defects can be detected using EC. This technique is not effective for monitoring internal defects.

Requirements: Minimum surface preparation is required. It requires the use of a diver to operate the probe underwater and an inspection.

Probability of detection: same as MPI.

3.2.5 RT (Radiographic inspection)

The working principle of this technique is related to the phenomenon of electromagnetic penetrating radiation such as X-rays and gamma rays penetrating in a piece of the specimen, the radiation is absorbed, and these rays are attenuated according to the material density and thickness. Unabsorbed radiation will flow through the specimen. This radiation penetrates through of material and influences the radiation-sensitive film on the other side, as illustrated in Figure 22. In the case of development, this film exposes the image of the interior section of the material that the radiations pass through. Less radiation will pass through the testing material if the specimen is thicker and denser, and vice versa. This method is being used to find internal, and surface defects in metallic materials, as well as material loss in a direction parallel to the radiation beam and welded connection [60].

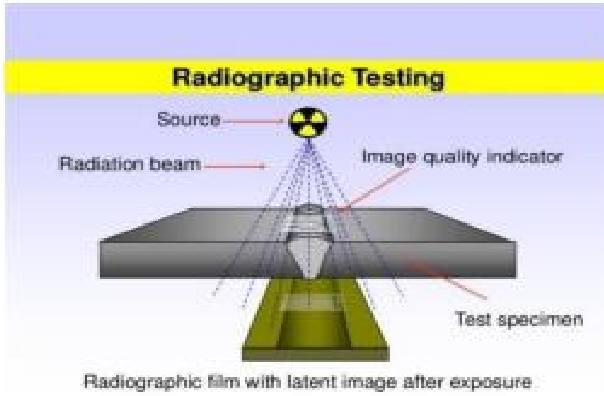

Figure 22: Radiographic Testing [56]

Monitoring capability: internal and surface defects, surface braking cracks, through-thickness cracks, severance and inspection of far surface and embedded cracks

Advantages [56]:

- Internal and surface flaws can be analyzed.
- Permanent record capability.
- Is effective for inspecting hidden areas.

Limitations [56]:

- The devices are cost effective (especially for x-ray sources).
- Sensitive to the orientation of detects.
- Radiation is dangerous to personal.
- Depth of cracks is not detected.

Maturity in the offshore Industry:

Maturity is assessed as HIGH, but it is considered to be dangerous for the personnel. The fusion of welded connections in metallic materials can be detected using RT.

Requirements: Requires minimum surface preparation.

Probability of detection: Good probability for gamma-ray radiation.

3.2.6 Acoustic Emission (AE) Monitoring

According to the principles of AE methods, an arrangement of sensors is utilized in order to identify distinctive sound patterns that may indicate the presence of structural defects in a specific area of the structure. Piezoelectric transducers are used on the structure's load-bearing surface to detect high-frequency elastic waves released from the material's flaw source. These frequency signals are subsequently transformed into electrical signals. Throughout structural loading, the output from the transducers is amplified by an external amplifier, filtered to remove any background noise, and then processed to detect any discontinuities. This technique is useful for local monitoring over a range of deeper depths in the structure because of the attenuation in the AE signal. It is possible to locate AE sensors either outside or interior to a structure [59] [61].

The AE has mainly been applied in offshore structures where there is a known high risk of fatigue cracking, corrosion and where monitoring this type of failure is difficult, unreliable, and/or expensive with other techniques. AE gives real-time information on fatigue crack initiation and growth and is mainly applied for the detection of fatigue cracks and weld defects at the early stage compared to other non-destructive techniques. It also has high sensitivity and accuracy [3] [59].

Figure 23 describe the AE components for monitoring the material under load or the state of stress. Strain energy is generated by the material as a result of the load acting on it, and the sensor located on the structure's surface measures this energy [59].

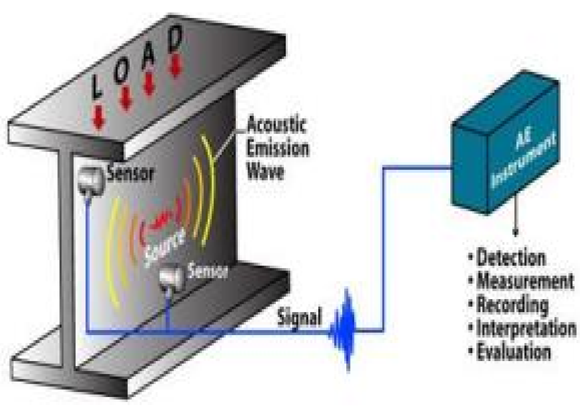

Figure 23: Acoustic Emission technique [59]

Monitoring capability: fatigue crack initiation, crack growth, surface-breaking cracks, through-thickness cracks, far and embedded cracks and corrosion**.**

Advantages [59]:

- It is a highly sensitive and comprehensive method of monitoring internal crack initiation and growth, as well as corrosion.

- In contrast to UT and RT, it does not depend on the size of the flaw.
- Real-time monitoring.
- It makes it possible to find discontinuities on large constructions during operation. (LPG tanks or storage tanks, for example).
- Flaw can be detected at the early stages.

Limitations [59] [3]:

- Proper evaluation can only be obtained when the signal is amplified, filtered from background noise, attenuation and other influences.
- The proper results can be achieved in case of no variation in environmental/operational loads.
- Signals with more than half of the Nyquist frequency frequencies are aliased (folded back) into the lower frequency range. In the worst-case scenario, the original signal will be significantly distorted as a result of this. If a lower sampling frequency is chosen, the system's low pass filters must be adjusted to a frequency that is significantly lower than Nyquist.
- For jacket platforms, AE cannot be applied to detect existing defects (when the crack is growing).
- AE sensors should be positioned relatively close to the expected defect source in order to obtain applicable AE signals from material.

Maturity in the offshore industry:

The AE is an appropriate technique for safety monitoring of critical members and is mostly applied on the structure's surfaces at an early stage [3].

Requirements: Requires periodic maintenance and calibration. Amplification and filtration methods are required to remove background noise for accurate evaluation.

Probability of detection: AE technique has a high level of maturity for integrity monitoring and can be placed on the ground or embedded. However, because of the high sensitivity, it is subjected to a lot of background noise; therefore, filtration and amplification methods are required for accurate evaluation [3] [61].

Case study for proper localization of AE sensors are displayed in Chapter 5.

3.2.7 Acoustic Fingerprinting

The working principle of acoustic fingerprinting is based on acoustic waves, in which these waves are transmitted to the detect structure and then, the reflection time of the acoustic signals listens for any discontinuities. This technique is considered active because it requires the transmission of acoustic waves, in contrast to the passive basic acoustic emission method. Continuous SI monitoring could be integrated into any platform using this technique.

Monitoring capability: surface-breaking cracks, through–thickness cracks.

Maturity in the offshore industry: Untested in major structures.

Advantages [3]:

- Any platform can be updated with this continuous SI monitoring.
- This method would be able to determine the member or potentially structural location where the damage is occurring.

Limitations [3]:

- If the technology is confirmed, it will most likely be sensitive enough to detect only severed members.
- Unproven technique.

Requirements: Continuous calibration of the equipment would be required in order to run the operation and achieve performance standards.

Probability of detection: It is expected to show high PoD, but has not still proved in offshore industry.

Non-destructive techniques discussed above are local damage techniques and give real-time monitoring to detect discontinuities through service life oil and gas platforms. These techniques are mainly applied to ageing jacket platforms. Following global monitoring techniques, the first three ones (GPS, RAMSTM, Air gap monitoring) are focused on monitoring global displacements of risers, mooring lines and air gap monitoring, respectively. The other one focus on the main presence of damage in the structure.

3.3 Global positioning system monitoring

The main objective of an Integrated Marine Monitoring System is to give real-time information regarding the position of floating offshore platforms. GPS is a highly-developed technology with real-time accuracy, which change around 10 meters horizontally. It is the best way to investigate and calculate vertical displacement or lowering and rising of platforms in order to assess the relative position of stations [3]. A GPS system consists of several components, including a controller, sensor, thruster and power system. The sensor transforms information to the controller about the platform's position and environmental parameters [62].

The procedure is highly effective for any floating platform that requires an accurate position to be monitored. The following are two examples of applications:

1. Semi-submersibles: the position of the structure can be founded, and an alert can be activated if the structure deviates with respect to reference point. The operator would be warned if there's any severe problems with the mooring system.
2. FPSOs: periodic monitoring of the position of the FSPO vessel from an assigned reference point. In addition, relative position is used to check if excessive loads impose risers [3].

Monitoring capability: loss of position, loss of air gab.

Maturity in the offshore industry: It is a commonly used in the offshore industry.

Advantages:

- ❖ It is a highly accurate and reliable method that can be used for surveying and mapping a range of work.
- ❖ Wind speed and direction, and height of wave can be obtained with this technique.

Limitations:

- ❖ The GPS signal is significantly influenced by the surrounding atmosphere.
- ❖ Recharging and replacement of battery are required frequently.

Requirements: Minimum maintenance is required.

Probability of detection: It is for defining the displacements of large platforms. Then detecting damage from deck movements is arguably very difficult.

3.4 Riser and Anchor Chain Monitoring with RAMS™ system

Riser and anchor monitoring systems (RAMS™) comprise a sonar array deployed to the pattern of risers or anchor chains, and structural integrity and position of mooring lines and risers can be monitored by using this system. The system collects and analyzes signals from parts within the monitoring area. This data is later used to define the location of these parts.

If there is an issue with the platform's mooring system, Riser and anchor monitoring system will warn the operator of any displacements that exceed predetermined limitations. [3].

RAMS™ is an extensively employed 360° anchor-chain and riser integrity monitoring system developed exclusively for (FSPO). The RAMS™ system has no mechanical moving parts, making it appropriate for long-term deployment compared to other mooring line and riser monitoring systems. No additional sensors are required to install on risers or mooring lines, ensuring that existing infrastructure is not damaged. RAMS™ provide real-time monitoring and continuous data [63].

Monitoring capability: Position of risers and mooring lines.

Maturity in the offshore industry [3]: This technique is widely used in FSPO platforms.

Advantages [63]:

- Real-time monitoring and continuous data.
- no additional sensors are required to connect mooring lines or risers.
- The ability to set user-defined alerts to provide early notification of excessive.
- Capability for long-term deployment and moving parts is not required.
- Continuous reading for the examination of riser/bend stiffener.

Proven technologies and deployments in the field.

Limitations [63]: For a variety of reasons, the transducer may not periodically identify a significant percentage of the reflected beam.

Requirements: Requires relatively minimal maintenance.

Probability of detection: It is for defining the displacement and position of FSPO. Then detecting damage from deck movements is arguably very difficult.

3.5 Air Gab Monitoring

The air gap is determined as the difference between the platform datum (the lowest point of the cellar deck) and the maximum extreme water level (often 100 years). Air gap sensors can provide an accurate estimate of wave height on, especially semi-submersible platforms. The air gap sensor sends out a microwave signal and receives the echo signal from the sea level [3] [64].

The main approach of this technique is to measure the air gap at scheduled times, like every three years. The readings are then compared, and any concerns associated with a reduced air gap are discussed [3].

The definition of Air Gap and Air Gap sensor is shown in figure 27.

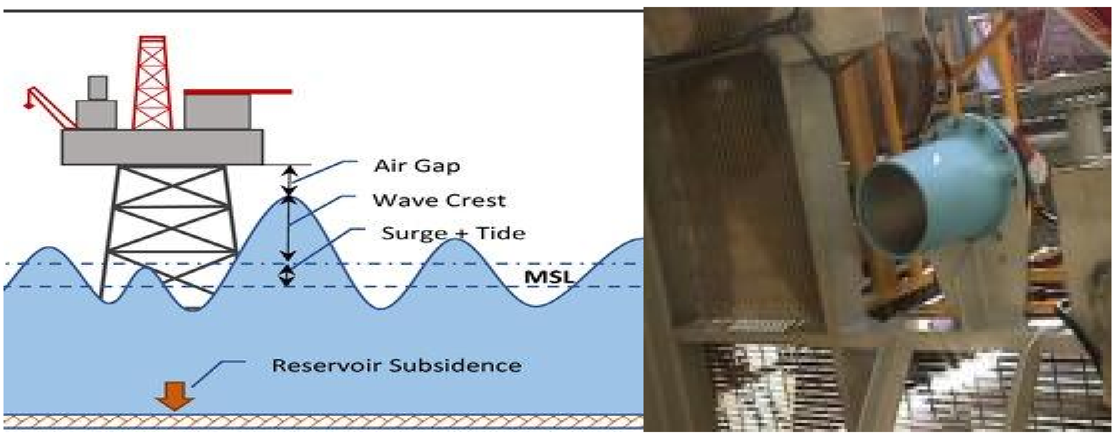

Figure 24:Air Gap and air Gap sensor [65]

Monitoring capability: Loss of air gap, estimation of wave height.

Maturity in the offshore industry:

Air gap monitoring has been performed for years; therefore, the procedures have been changed significantly throughout that period. This is, nevertheless, a common monitoring approach that is frequently used in the offshore industry and is highly accepted.

Advantages: 24hrs monitoring capability.

Limitations: A need for the calibration and maintenance of surface-based measurement equipment for the ongoing recording of wave height.

Requirements: Experienced operators and calibration during ongoing operation are required to calculate measurements.

Probability of detection: It is for defining the air gap of platforms. Then detecting damage from deck movements is arguably very difficult.

3.6 Strain Monitoring

Strain monitoring is used to identify the stress or loading regime in a structure's component. Traditional strain gauging, fiber optics, and stress probes are examples of strain measurement systems. The impact of stress on the materials can result in strain. Therefore, Vertical bending, horizontal bending, torsion, vertical shear force, and longitudinal compression forces cause [66]. Stain is calculated ratio change in length (ΔL) and initial length(L):

$$\varepsilon = \frac{\Delta L}{L} \qquad (3.3)$$

The objective of stain monitoring is to analyze local stress variations in order to get a better understanding of local structural loading and/or stress regimes. Local hot spot stresses can then be computed using numerical modelling [3].

FBG sensors for strain monitoring are considered most acceptable compared to other strain gauges because they have better resolution and range, withstand water and corrosion resistance and are less sensitive [67].

Monitoring capability: local stress, bolt loosening.

Maturity in the offshore industry: It is commonly used in several industries, including the offshore sector**.**

Advantages: It has high accuracy and efficiency.

Limitations:

- Equipment, specifically cabling up the legs into the splash zone, is more sensitive to environmental problems.
- Sensitive to gauge position in regions with strong stress gradients.

Requirements: Periodic maintenance is needed to ensure integrity and connectivity of strain gauges.

Probability of detection: High PoD.

3.7 Fatigue gauge

CrackFirst™ (fatigue damage sensor) was developed exclusively for welded steel connections and is presently accessible from Strainstall. In contrast to a traditional strain gauge, which measures the amount of strain at the place where it is attached to the structure, CrackFirst™ calculates the amount of fatigue damage that occurred to the structure. Cracks in jacket structures are most frequently reported on the nodes. CrackFirst™ fatigue sensors with 0.25mm steel shim are placed on nodes and also up to 10mm from the weld in the node [3].
The sensor is designed in a way that the extent of crack propagation in the shim is related to the cumulative fatigue failure for a welded joint subjected to cyclic loads, such as ships, moving machinery, bridges, cranes. These sensors can clearly identify any uncertainties in their fatigue life performance on a structure (assuming the sensor can be placed near the weld toe). It is also possible to operate the system remotely, and data can be received via a wireless device [3]. In addition, the expected fatigue design life of a structure can be estimated, and the remaining life of particles in structures can be identified by CrackFirst™ sensors. Figure 28 shows the location of fatigue gauges.

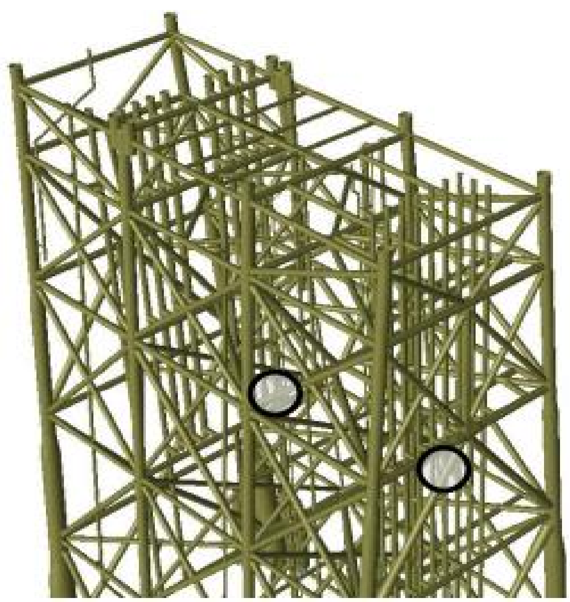

Figure 25: CrackFirst™ Location [68]

Monitoring capability: Fatigue cracking.

Maturity in offshore industry: Limited used in oil and gas platforms.

Advantages [69]:

- Provide high accuracy.
- Increase overall operational efficiency.
- Give correct info about the fatigue in the structures.

Limitation [69]:

- Due to varying environmental conditions, specifically underwater, connecting to the structure may be complicated.
- It may be tough to mount the sensor relatively near the weld toe.
- Failure to identify a lack of adhesion may result in inaccurate measurements.

Requirements: Sensors should be placed properly before installation. When sensors are damaged, they cannot be replaced.

Probability of detection: High PoD

3.8 Vibration-based monitoring

The vibration-based monitoring technique is primarily used as a global monitoring technique to analyze structural damage and degradation.

Vibration-based approaches are the basis of widespread Structural Health Monitoring (SHM) approaches, which are used across different fields of application. They generally rely on accelerometers to capture the global vibrational behavior of the structure. The frequency change is evaluated to identify damage in the structure during the inspection. The next equation is the definition of the natural frequency (f) in an offshore jacket platform [70]:

$$f = \frac{1}{2\pi}\left(\frac{k}{m}\right)^{0.5} \qquad (2.4)$$

The frequency values change with global properties such as the stiffness (k) and the mass (m), which are impacted by the damage in the offshore structure. The vibration-based approach is primarily relying on this relationship in order to find any displacement in the structure. The presence of damage is inferred from a deviation from the usual dynamics (generally because there is a local decrease in stiffness).

An alternative to NDT techniques is the Vibration-based technique for structural integrity monitoring of ageing jacket fixed platforms. The vibration-based technique presents as "**natural frequency response monitoring (NFRM)**" in a practical case. The response of the jacket structure to wave loads is being monitored. This method evaluates the change in natural frequency of the jacket structure, which allows it to analyze a partial loss of structural integrity caused by the natural frequency shift. The frequency at which a structure vibrates is determined by the stiffness and mass relationship as described above. For instance, damages such as cracks, flooded members according to through-thickness and connection loss in the structural members due to fatigue failures result in a shift in stiffness and mass. The change due to global properties is then captured by multiple signals. NFRM sensors are mounted on the platform's topside, where the degree of motion is estimated to be the greatest. Larger noises can be detected, which helps to decrease the result of background noise. Fast Fourier Transform (FFT) techniques are being used to record the motion data. This procedure gives a frequency spectrum for each time trace, allowing for the detection of peak motion frequencies. Figure 29 explains the FFT procedure [71].

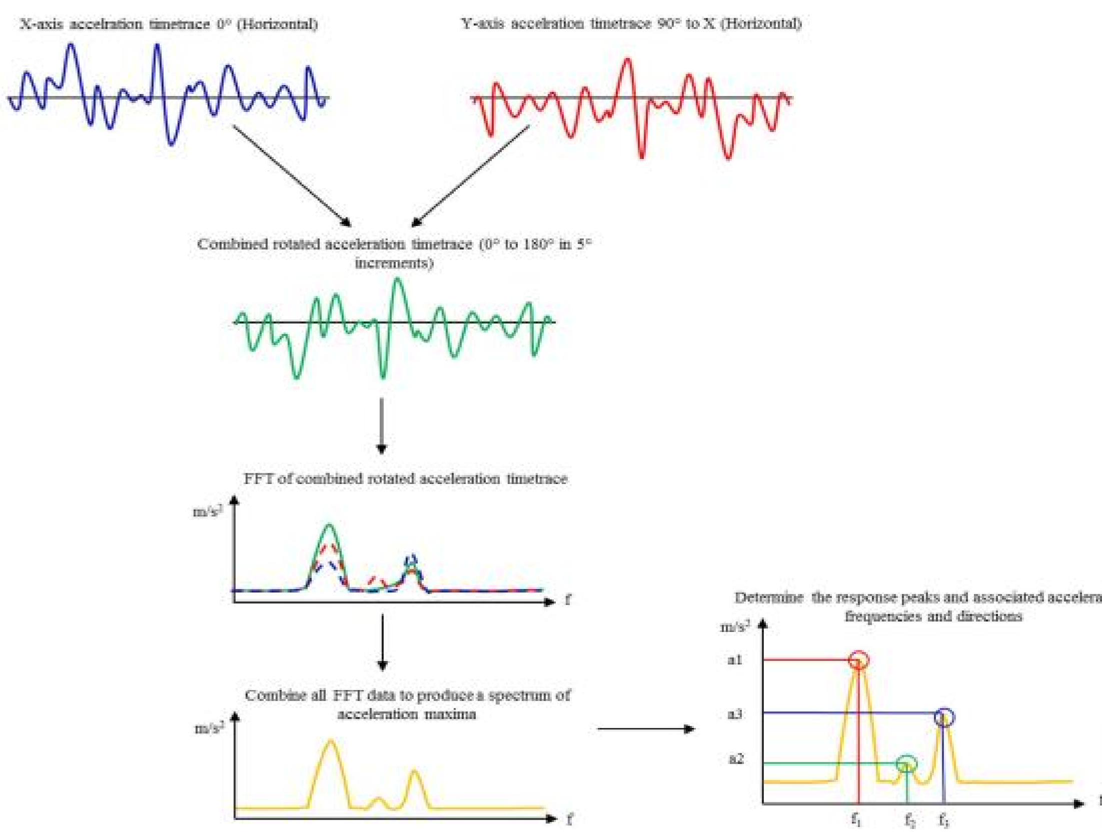

Figure 26: Data Processing(FFT) [71]

The peak frequency is measured as part of the NFRM process. As demonstrated in Figure 30, structural failure generates a change in structure stiffness, which subsequently causes a change in peak frequency [71].

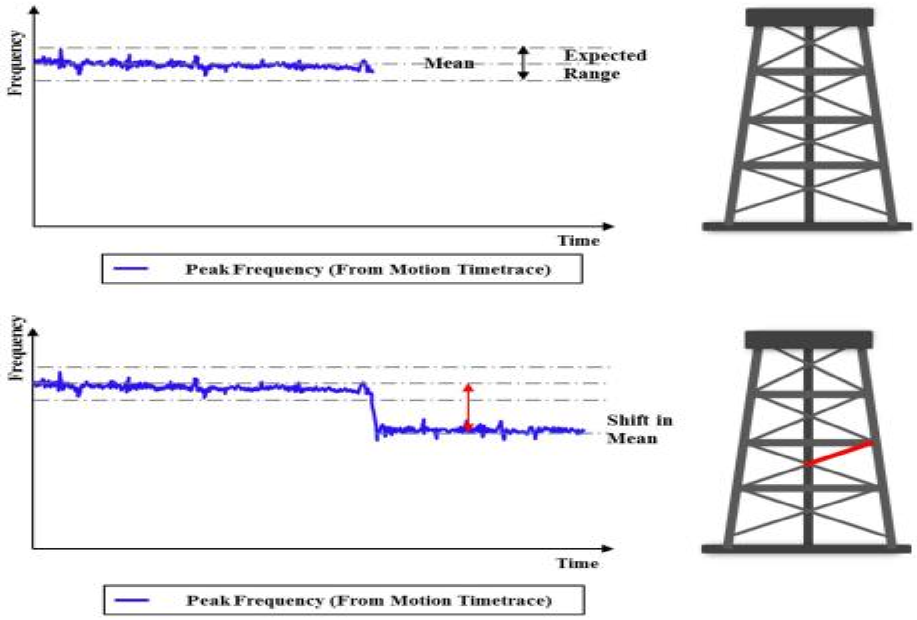

Figure 27: Detection of loss of integrity using NFRM [71]

Monitoring capability: member severance, 80% through-thickness cracks in low redundancy jacket structures.

Maturity in the offshore industry: Over 85% of platforms in the North Sea are classified as jacket fixed platforms, which are well suited to the NFRM [3].

Advantages [3]:

- Provide a pseudo-real-time understanding of structural status following environmental and other unexpected conditions to the operator.
- In low redundancy systems, NFRM can also detect 80% through-thickness cracks.

Limitation [3]: The technique is only sensitive to find frequency changes around 0.5 percent. It means that It is difficult to detect small flaws with this technique.

Requirements: Minimal. Once installed, an NFRM system needs no further intervention apart from routine maintenance checks and data interpretation from an onshore facility in case of an unexpected structural event.

Probability of detection: If the frequency change is less than 0.5%, failure would be undetectable [3].

Chapter 4. Opportunities for development of SI Monitoring technologies for life extension

Life extension is the procedure of extending the design lives of structures that have already passed. It needs a thorough understanding of the state of the structures, as well as damages such as fatigue, cracking, and corrosion that may occur. There are some components that are hard to detect using conventional methods. This constraint on structural integrity knowledge for the life extension stage is important, and opportunities for SI monitoring technologies to be applied to these difficult-to-inspect objects are critical. The following are descriptions of these parts and suggested SI monitoring techniques:

1. Risers: The riser is a significant part of an oil and gas platform. It is a vertical pipeline that runs the length of the jacket and is used for the transportation of oil or gas. Production risers transport oil or gas from the seafloor to the surface. Offshore risers are exposed to more severe wave loading and are built-in corrosive conditions. The intertidal and splash zones on the riser are areas that are subjected to degradation, and as a result, corrosion is much more aggressive in this area and must be inspected continuously. Ultrasonic and eddy current testing would be more sensitive for inspection of risers [72].

Flexible risers are composite structures formed up of a number of metal amours and polymeric layers applied in offshore platforms because of their high quality and the fact that they are easier to install and operate than their rigid risers. Flexible risers are also less expensive than rigid risers. Strain monitoring in flexible risers can be provided through the use of FBG sensing technology [66].

2. Structures located in splash zone:

The splash zone is an area of continuous wetness and drying created by tides and waves, and it is the most dangerous corrosion area in offshore structures. When it comes to monitoring this zone, visual testing is performed; however, the probability of detection of this technique is limited. It is possible to detect fatigue, wall thickness, corrosion condition of structures or materials using offline monitoring methods such as ultrasonic and magnetic particles. These methods can be used to control the risk and prevent accidents by detecting the structures or equipment at specific time intervals [66]. Although NFRM technique is useful for monitoring for full member severance of hidden components in the splash zone, cracks would be difficult to detect using NFRM [3].

3. Welded connection: Tubular steel joints are constructed using welding parts. Welding defects are common in these areas. Defects in weld connection occur over time due to high stress and cyclic loading of waves. That is why Fatigue starts to form cracks in these joints and also along the thickness of the members. Finally, the braces will separate from the chord members. There is also the risk of corrosion of steel in areas below ground where the CP system may be less efficient. Radiography Testing is commonly applied in metallic materials to detect substantial thickness (material loss) in a direction parallel to the weld joints [58]. Ultrasonic testing and NFRM are good options for monitoring welded connection [3].

4. Jacket legs: Most of the indicated cracks, buckling, and dents were found on the bracing system and jacket legs. So, the need for reliable SI techniques has been increased for these parts. Detecting the failures at the early stages in these parts is the objective of SI monitoring techniques. Acoustic emission is the most effective technique for monitoring jacket legs.

5. Pile sleeves/piles: Steel tubes in jacket platforms are anchored directly on the seabed by using piles. The piles support the platform and take on axial force (tension and compression) as well as lateral loads, which impacts perpendicular to the piles. The NFRM can be performed for SI monitoring of these members [73].

6. Grouted connection: Grouted connections are considered the best components in the offshore industry to improve structures' stability and transfer load between piles and the structure. The grouted connections are positioned slightly above the seabed, and as a result, they are always underwater and in contact with seawater. These are manufactured during the installation process and are consequently difficult to inspect during future inspections and testing [74].

7. Ring-stiffened joints: Ring-stiffened joints can be seen on a lot of platforms. The stiffeners give extra strength to resist static loads and are effective for the extension of fatigue life. Fatigue analysis of these joints has revealed that stiffeners do fail and that this does not display themselves externally until severe internal damage has occurred, resulting in a significant reduction in the efficiency of the joint. Ultrasonic testing can be applied to keep track of this situation.

8. Areas of Accumulated damage: Damage arising from accidental incidents that occur over time, such as ship collisions or fallen objects, can accumulate to the point where a member or joint's strength is reduced or entirely lost. A significant danger scenario for an offshore platform is the impact of falling objects or swinging loads during lifting operation by cranes. It is possible that the impact will occur with hydrocarbon-containing equipment or that it will occur directly on a structurally sensitive area of the installation. Individual damage is generally observed and repaired immediately after an event. Still, studies have shown that approximately 20% of such damage is only revealed during subsequent periodic inspections. By this time, it has often been covered by marine growth, making it difficult to find the location of the damage. The NFRM is the most effective technology available for detecting and monitoring large-scale damage shortly after an incident. However, the use of NFRM to assess for indentation or partial loss of strength is not a successful approach. These operations can be carried out by using long-range ultrasonic testing [3].

9. Deepwater members: In water depths more than 150 meters, diver inspection is not normally acceptable, and inspection is restricted to techniques. This issue can be managed with an ROV [3].

10. Wellhead flow lines: Due to the high cyclic loads caused by Xmas tree movements and flow-related vibrations, wellhead flow lines must undergo a thorough fatigue analysis [75].

11. Connection between the clamp and tubular member: Clamps are being used to strengthen jacket structure brace members or joints. They have been employed to add members, expand the capacity of current members, and restore the capacity of joint members that have been injured. Corrosion might occur at the connection between the clamp and the tubular member. Periodic inspection is necessary [76].

There is a list of SI monitoring techniques that can be potentially used for these parts, and additional critical parts are illustrated in Table 5.

Components	Expected failure mode	Potential SIM Techniques
Risers	Corrosion, crack	UT, Eddy current testing, FBG sensors
Structures located in splash zone	Corrosion, fatigue	UT, MPI, NFRM
Welded connection	Fatigue, crack, corrosion, buckling, dents, holes	UT, NFRM Radiography testing
Jacket legs	Crack initiation, Through-thickness cracks Widespread fatigue damage, Buckling	Acoustic Emission
Pile sleeves/piles	Fatigue, corrosion, buckling	NFRM, Fatigue Gauge
Grouted connection	Corrosion, loss of bonding of grout	Acoustic Emission
Ring-stiffened joints	Fatigue cracking	UT
Accumulated damage	Crack, dents	Long range UT, NFRM
Deepwater members	Corrosion, fatigue	ROV inspection
Wellhead flow lines	Fatigue	Fatigue gauge
connection between the clamp and tubular member	Corrosion	
Flare booms and vent stacks	strength reduction due to heat, fatigue cracks	Acoustic Emission
Conductor centralizers	Wear/Mechanical failure	Acoustic Emission
Weld toe	Fatigue	Fatigue gauge
Joint connections between support frames and column structures	Fatigue	Fatigue gauge

Table 5 Potential SI Monitoring Techniques for items which are difficult to inspect

Chapter 5. Case studies

5.1 System installation of AE sensors for jacket structures (Case study 1)

Proper selection of AE sensors is critical to getting accurate measurements. Besides choosing the right type of sensors, locating AE sensors in place is essential for jacket structures. The positions of AE sensors are dependent on the number of braces, nodes, and joints present in the structure. These points are characterized as critical points in the structure and are needed to monitor to increase integrity. In addition, AE sensors are dependent on the number of bracings and joints in the structure.

It is advisable that AE sensors can be mounted either externally or inside in dry hull members [3]. Installing the AE sensors in this place is necessary in order to monitor any potential crack propagation on the severed part that is already impacted by cracks. There are four AE sensors that are externally located close to nodes and joints, as indicated by red lines in Figure 24. The cables from the sensors are stored in a box. These cables are attached to a tension cable which is connected to topside [77].

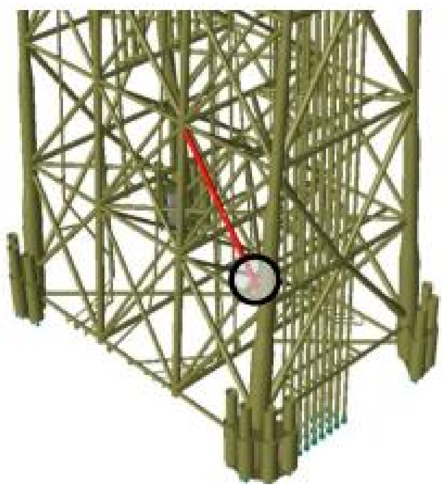

Figure 28: Location of AE sensors in severed member [77]

Figure 25 shows the location of AE sensors for jacket platforms in three types of bracing systems: X-shape, V-shape and single shape, respectively, according to the SAP200 program [78]. The certain positions for the AE sensors are colored with the red circles in figure 25. A maximum 4-meter distance is acceptable between each sensor. The maximum distance between sensors should not exceed

4 meters, as this is the only way to receive acoustic signals accurately and obtain effective localization to find defects [79].

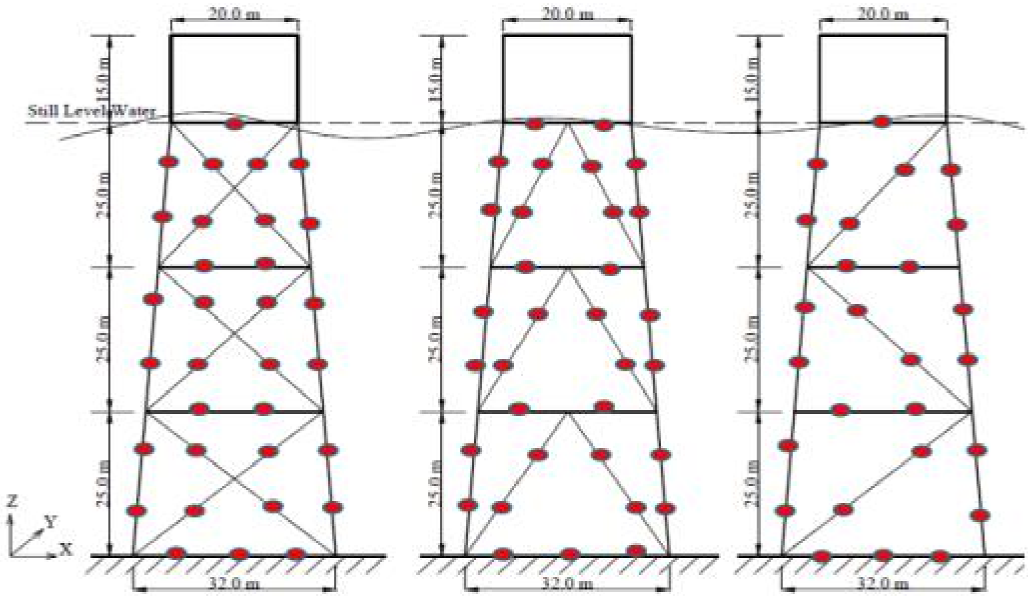

Figure 29: Proposed installment of AE sensors on Jacket structure's surface [79]

Figure 26 displays another example installation for AE sensors for a J-structure design, in which they are positioned inside the jacket structure's legs. A few AE sensors are used to monitor fewer areas for detecting flaws in this method. It also avoids attenuation due to refraction because the acoustic waves do not pass through water to arrive at the sensors. As a result, installing AE sensors inside legs can produce more accurate signals from other acoustic sources [63].

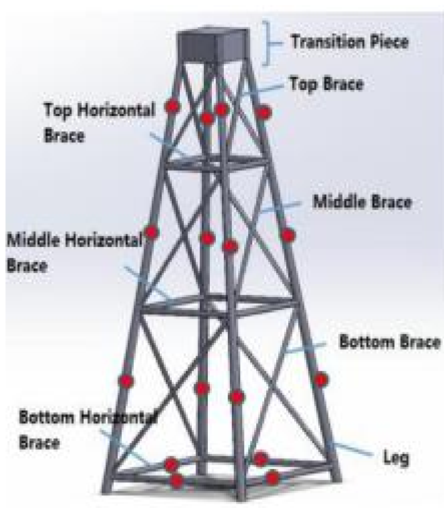

Figure 30: Proposed installment of AE sensors inside legs members of the jacket J structure [80]

5.2 Proper SI monitoring techniques in the offshore platform of Guneshli field Case study 2

A disastrous fire broke out on an offshore platform-10 in the Guneshli field in offshore Azerbaijan on December 4th, 2015. The oilfield, which predominantly produces oil and some gas, has been performed since the 1970s and was restored in the 1990s.

A heavy windstorm in the splash zone triggered damage in a natural gas riser, was shaken out the platform’s leg and caused the fire. This fire incident resulted in the deaths of 16 workers [81].

Figure 31: Fire in Guneshli platform [81]

These accidents increased the role of integrity monitoring techniques around the world. Structures positioned in the splash zone are considered to have a higher failure rate compared to structures located in other places. The area directly above and below the sea level is referred to as the "splash zone." Offshore risers are exposed to more extreme wave loads because of deploying in corrosive conditions. Corrosion is more severe in the intertidal and splash zones on the risers because they are more likely to get damaged. If the risers are inspected routinely with non-destructive techniques such as long-range UT and eddy current, visual inspection, failures such as cracks, corrosion in risers could be found at the earlier stage. The riser could be changed or repaired before the fire occurred. This

Guneshli platform has been used after repairing the damage from the fire. Therefore, SI monitoring techniques should be implemented to maintain integrity and increase service life, especially in risers and welded connections.

This platform is a fixed jacket platform, and nowadays, different types of failure mainly occur in this platform due to ageing. On the other hand, this jacket is more sensitive to failures after the fire. Common crack initiation occurs in welds, present surface scratches and heat-affected areas in the material. Corrosion and fatigue cause damage and crack in the weld connections. Different SI techniques can be applied to maintain structural integrity in this platform:

Magnetic particle inspection is a cheaper and safe method to determine failures in structures. MPI is used to detect cracks for the first time. However, the accuracy of this method is lower than ultrasonic testing. If Additional detection is needed, Ultrasonic testing is used. With ultrasonic testing, embedded cracks can be detected, and the thickness of the wall can be measured to identify the level of corrosion in these structures.

For the items located in splash zone such as risers, visual inspection by ROV should be implemented routinely, and wall thickness can be measured by long-range ultrasonic techniques, as shown in Figure 17.

Robust noise monitoring, which is the combination of acoustic and vibration signals, could be used to identify the presence of different abnormalities in a platform's technical condition at an earlier stage before they have a possibility of causing significant damage. Figure 32 displays the robust noise monitoring system in operation at the beginning of the latent period of the Fixed Platform's shift into an emergency condition. Data about the technical condition of the platform’s parts can be obtained from received signals from acoustic (Accutech AM20) vibration-based sensors (BeanDevice AX-3D). These sensors are mounted on all critical items of the offshore platform. All received data are collected in the device of the CetanWay Controller. These collected data from acoustic and vibration sensors are then analyzed in the Getac A770 industrial computer. The cracks, corrosion and other failures can be detected with this data at an earlier stage [82]. This technique is useful to identify failures in offshore structures from the earlier stage, which can cause significant damage following time.

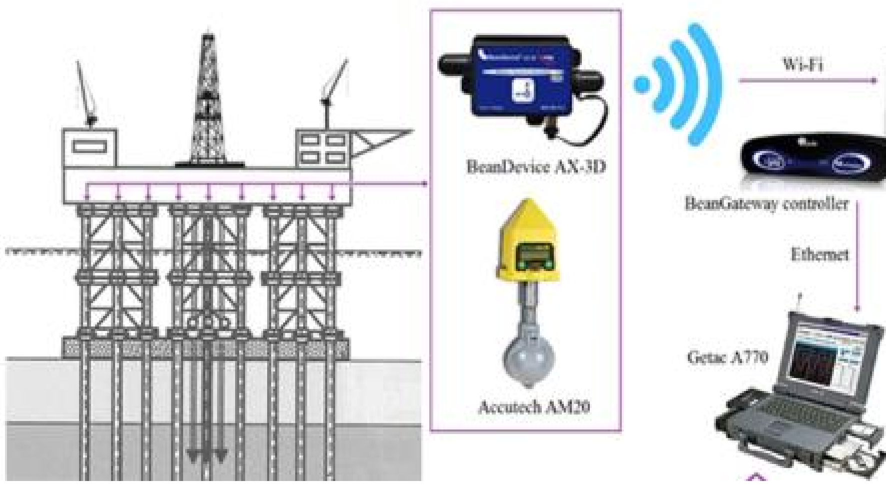

Figure 32 : Robust noise monitoring system (combination of vibration and acoustic sensors) [82]

Conclusion with future recommendation

1. The majority of offshore jacket structures in the North Sea and the Caspian Sea are running beyond their service life and must be reviewed and upgraded in order to potentially extend their service life. There is a number of codes and standards such as ISO, NORSOK, DNV that can make reference for SI monitoring. Different offshore structures, their design, members, critical parts have been reviewed.

2. The platforms are faced with several types of loads, such as gravity loads, hydrostatic loads, environmental loads, accidental loads, and these loads cause fatigue in offshore structures. Fatigue results in the crack, principally at welded connection by growing through different stages and leading to severance. Fatigue can be estimated through Hot-spot analysis and S-N curves which is essential for choosing proper SI monitoring techniques

3. Several SI monitoring techniques have been analyzed in this chapter. These techniques can be classified into two parts: Local and global monitoring techniques. Global techniques are used for monitoring of entire structure, while local techniques are limited to specific points where the damage occurred. However, Local techniques have high accuracy and efficiency compared to global techniques. GPS and RAMSTM as global techniques are mainly used for detecting the position of semi-submersible and FSPO platforms. Acoustic fingerprinting has not already been tested in the offshore industry, and they are considered as unproven. Acoustic emission technique has been indicated during the tests that it gives real-time monitoring for finding small defects in steel structures such as yielding or crack signals. It allows defining cracks in the early stages of development, and proper corrective measurements can be carried out before significant damage occur. While Ultrasonic testing is mainly used for detecting wall thickness, it has a monitoring capacity to detect even embedded cracks. Other SI monitoring techniques such as MPI, Eddy current and NFRM are used for surface-breaking cracks. Although Visual testing by ROV, camera system can detect visible and surface cracks, it is considered the most effective method because of low cost and immediate results. Full-member severance can be obtained by NFRM.

AE, UT, RT, GPS, Air gap monitoring, strain monitoring and RAMSTM have a high probability of detection.

4. SI monitoring techniques can be used to detect some critical parts which are difficult to inspect. These include welded connection, grouted connection, pile sleeves, ring-stiffness joints, items in the splash zone, etc. Life extension can be achieved with inspection of these parts.

5. 2 case studies have been carried out in this thesis study. In the first case study, the location of AE sensors to monitor potential cracks. These sensors are recommended to install the legs members. In this way, the number of AE sensors can be reduced, attenuation can be avoided, and accurate data can be achieved. In the second case study, fire in Guneshli Platform and required SI techniques after repair to maintain the structural integrity of the ageing platform have been reviewed. Ultrasonic testing is required in most cases to detect wall thickness and exact millimeters of length. But, it is a high cost. That is why MPI is used to detect cracks for the first time. If Additional detection is needed, Ultrasonic testing is used. ROV and long-range ultrasonic testing are SI techniques that can be used to analyze risers routinely. Robust noise monitoring, which combines acoustic emission and vibration-based techniques, could be the best monitoring technique for detecting failures earlier.

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Appendix A: Comparison of Characteristics of Structural Monitoring Methods

Monitoring Technique	Working principle	Monitoring Capability	Advantages	Limitations	Maturity in offshore industry	Requirements	Probability of detection
Visual Testing	It is carried out by personal workers by using ROV , borescope to detect major damage	Visible cracks, dents, abrasion, surface corrosion, erosion and surface-breaking cracks	simple and quick results, low cost procedure	Only surface discontinuities can be applied. Cannot detect sub-surface flaws	High maturity to detect cathodic protection condition of the surface	Advanced technology and highly skilled personnel are needed	Less reliable for detecting size of crack
Ultrasonic testing	Ultrasonic signals is sent to specimen by transducer and reflected signal is transforming to electric signal for reading	Wall thickness, fatigue crack detection, through-thickness and embedded cracks, severance , members in splash zone	Small millimeter thicker cracks can even be detected. Permanent reading can be achieved and exact location can be detected.	So expensive Irregular-shaped materials are difficult to detect	Mainly used for wall thickness and welded connection	Experienced operator and advance technology are needed. Couplant is required in most cases	More reliable to detect fine cracks
MPI	Surface cracks can be detecting by creating local magnetic leakage fields	Surface-breaking cracks, through-surface cracks sometimes	Low cost immediate result	Only available for ferrimagnet materials Embedded cracks cannot be detected	Is mainly used for surface discontinuities and welded connection	Minimal preparation for cleaning	POD for underwater is more difficult than above water
Eddy current testing	In case of cracks, eddy currents change in applied material	Surface-breaking and through-surface cracks	Real –time monitoring No probe required	Embedded cracks cannot be identified Expensive Requires diver to operate inspection	Only available for surface discontinuities	Presence of driver and minimum surface preparation	Same as MPI
Radiographic testing	Attenuation of electromagnetic radiation due to material thickness and density. Less thickness means less radiation	From surface to embedded cracks and severance can be detected	Permanent record Good for hidden areas	Expensive Harmful for human body, RT cannot detect depth of cracks	Is used for only special cases such as discontinuities of weld connection	Minimum surface preparation	High POD for gamma-ray sensors

Acoustic emission monitoring	Emission of waves from flaw material that is under deformation	From early stage of crack to final stage, surface and embedded cracks and corrosion	Independent from size of defect Real-monitoring Sensitive SIM technique	Wrong data can be gained because of background noise Existing effects is difficult to detect	Is mainly used at early stage of cracks	Periodic maintenance. Amplification and filtration are required to remove noise	High probability of detection
Acoustic fingerprinting	Transmitting of acoustic waves to structure and listen any abnormalities to detect discontinuities	Surface-breaking and through-thickness cracks	Continuous SI monitoring and identification of possible structural locale	Unproven technique If proved, It would sensitive only fully severed members	untested	Continuous calibration and Periodic maintenance are required	unproven
Global positioning system monitoring	Alarm activate in case of deviation from reference point	Position of structure, Loss of air gap	Wind speed and direction and accurate data can be achieved	GPS sensors is influenced by atmosphere	Is widely used in offshore industry for detection of position	Minimal maintenance requirement	It is for defining position of floating structures
Riser and Anchor Monitoring, RAMS^{TM} system	Consist of sonar array which deployed externally pattern of risers or anchor to monitor their position	Position of mooring lines and risers	Continuous monitoring Fully automatic system	Significant amount of reflected signals cannot be obtained sometimes	RAMS^{TM} is widely used in PSPO platforms	Minimal maintenance is required	It is for defining position of FSPO structures
Air gab monitoring	Air gap sensor emit and receive microwave signals from water surface	Loss of air gap	7/24 hours reading	Requires professional operator to carry out operation	High maturity	Experienced contactor and calibration required	It is performed for air gap monitoring
Strain Monitoring	Strain measurements which caused by action of stress	Local stress, bolt loosening	High accuracy	Highly dependent position of sensors and environmental condition, requires calibration	Widely used	Required periodic maintenance	High POD
Fatigue gauge	CrackFirst^{TM} is based on sensing the amount of fatigue damage in materials	Fatigue cracking	Give correct info about the fatigue in the structures	Depend on environmental condition and is difficult to detect the amount of failure underwater	Limited information in offshore platforms	Sensor should be placed properly.	High POD
Vibration-based monitoring. NFRM in practical case	Vibration of structure by frequencies. The change in frequencies shown decrease in wall thickness and loss of member connection	Member severance 80% through-thickness cracks	Real-time monitoring Available in detection of splash zone and weld connection	NFRM cannot identify minor defects	In 85% of North Sea platforms, this technique is used	Minimal maintenance	If the frequency change is less than 0.5%, failure would be undetectable

Appendix B: Qualitative Review of relevant SI Monitoring Techniques

Table 1: Underwater

Damage mechanism	Assessment of current inspection techniques	**Complementary SI Monitoring techniques**										
		Visual Inspection	AE	Pulse Echo UT	Long range UT	MPI	Eddy current	RT	Fatigue gauge	NFRM	SM	Acoustic fingerprinting
Surface-breaking cracks	Presence of diver is required											
Through-thickness cracks	Available ROV is widely used, in other methods, presence of diver is required											
Far-surface or embedded cracks	Presence of diver is required											
Severance	Available ROV is widely used, in other methods, presence of diver is required											
Severe external corrosion	Available ROV is widely used											
Severe local corrosion	Available ROV is widely used											
Bolt loosening	Available ROV,CVI is widely used											
Scour, Debris	Available ROV, CVI is widely used											
Buckling, dents, holes	Available ROV,CVI is widely used											
Marine growth	Available ROV,CVI is widely used											

*green- Highly effective.
*yellow- medium effective.
*brown-low effective.
*CVI-close visual inspection.
*ROV- remotely operated vehicle.

Table 2: Topsides

Damage mechanics	Assessment of current inspection technologies	Complementary SI monitoring										
		Visual testing	Pulse Echo UT	Long range UT	AE	MPI	Eddy current	RT	Fatigue gauge	NFRM	SM	Acoustic fingerprinting
Surface-breaking cracks	Possible techniques accessible RAT maybe required											
Through-thickness cracks	Possible techniques accessible RAT maybe required											
Far-surface or embedded cracks	Possible techniques accessible RAT maybe required											
Severance	Possible techniques accessible RAT maybe required											
Severe external corrosion	Possible techniques accessible RAT maybe required											
Severe local corrosion	Possible techniques accessible RAT maybe required											
Bolt loosening	Possible techniques accessible RAT maybe required											
Breaking of coating	Possible techniques accessible RAT maybe required											

*green- Highly effective
*yellow- medium effective
*brown-low effective

*RAT- Rope Access Technician

Table 3: Moorings

Damage mechanism	Assessment of current inspection techniques	Complementary SI Monitoring								
		Visual Inspection	AE	Ultrasonic testing	MPI	Eddy current	Fatigue gauge	SM	RAMS™	GPS
Surface-breaking cracks	For the detailed detection, anchor chain should be raised for inspection with CVI									
Through-thickness cracks	For the detailed detection, anchor chain should be raised for inspection with CVI									
Far-surface or embedded cracks	For the detailed detection, anchor chain should be raised for inspection with CVI									
Abrasion	Available ROV is widely used,									
Severe external corrosion	Available ROV is widely used									
Severe local corrosion	Available ROV is widely used									
Deviation in position of mooring lines	RAMS™ and GPS is widely used									
Bolt loosening	No accessible method									
Scour, Debris	Available ROV, CVI is widely used									
Buckling, dents, holes	Available ROV,CVI is widely used									
Marine growth	Available ROV,CVI is widely used									

*green- Highly effective.
*yellow- medium effective.
*brown-low effective.
*CVI-close visual inspection.
*ROV- remotely operated vehicle.