Universitetet i Stavanger

Faculty of Science and Technology

Master's thesis

Study program/ Specialization: Constructions and Materials/Offshore Constructions	Spring semester, 2016 Open
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Thesis title:

Structural Health Monitoring of Offshore Jackets

Credits (ECTS): 30

Keywords:	Pages: 98
Structural Health Monitoring	+ Enclosure: 5
Jacket structure	
Instrumentation	Stavanger, 14/06-2016
Integrity assessment	

Front page for master thesis
Faculty of Science and Technology
Decision made by the Dean October 30th 2009

ABSTRACT

The aim of what is reported is to explore how developments within SHM can be applied as a tool for assessing the structural integrity of offshore jackets. More specifically develop a proposal for monitoring an existing jacket in a cost-effective manner. New research has been evaluated with regards to both local and global damage detection methods. The suitability of combining those two methods is investigated. The work done in this thesis was primarily based on available articles and conference papers. This thesis covers a literature survey of SHM in general and for jacket structures, including a proposed methodology describing how to set up a monitoring system on an offshore jacket structure. This methodology is thereafter implemented and used to design a monitoring system for a fictional platform on the Norwegian Continental Shelf (NCS).

It is concluded that due to increased research there is possible to make more cost effective and more robust SHM systems in the near future. However, even though there is an increased research effort in SHM of offshore jacket structures, real experiments have to be done to verify their applicability. Also, it should be focused on further development and tests regarding measurement methods and sensor technologies.

PREFACE

This thesis is completed during the spring of 2016 at the Department of Mechanical and Structural Engineering and Materials Science at the University of Stavanger. The work is proposed and supported by DNV GL, Stavanger.

During the work of this thesis I have familiarized with NORSOK and ISO standards relevant to SHM, gained an understanding of different sensor technologies and how SHM systems may play a major part in the structural integrity management of offshore assets in the future. These learnings are helpful for me in the future and also hopefully a solid contribution to the research of future SHM systems for DNV GL.

First I will give a special thanks to my supervisor at DNV GL, Bjørn Thomas Svendsen for all the valuable discussions and help along the way. I am also very grateful to my coordinator at the DNV GL office Ole Gabrielsen for giving me the opportunity and means to write this thesis. Not to forget, I will like to thank the whole team of engineers at the department of offshore structures for inputs and their sharing of knowledge during my stay.

At last I will thank my supervisors at UiS, Hirpa G. Lemu and S. A. Sudath C. Siriwardane for excellent guidance of my work during the semester. Their help and guidance have been much valuable for me and is something I couldn't be without.

Stavanger, June 2016

Herman Vestli

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LIST OF ABBREVIATIONS AND ACRONYMS

AET	Acoustic Emission Testing
AIS	Artificial Immune System
ALS	Accidental Limit State
CF	Corrosion Fatigue
CM	Condition Monitoring
CMSE	Cross-modal Strain Energy
DET	Rating Detection
DFF	Design Fatigue Factor
DFI	Design Fabrication Installation
DFO	Documents For Operation
DGN	Diagnosis Confidence
EAC	Environmentally Assisted Cracking
ER	Electrical Resistance
FBG	Fiber Bragg Grating
FDD	Frequency Domain Decomposition
FEMU	Finite Element Modal Updating
FFT	Fast Fourier Transform
FLS	Fatigue Limit State
FM	Fracture Mechanics
FMD	Flooded Member Detection
FMS	Fleet Management System
FPSO	Floating Production, Storage and Offloading
FRS	Frequency Response Spectrum
FT	Fourier Transform
GWT	Guided Wave Testing
HE	Hydrogen Embrittlement
HSE	Health & Safety Executive
IBCM	Instrument Based Condition Monitoring
IVHM	Integrated Vehicle Health Monitoring
LME	Liquid Metal Embrittlement
LMS	Least Mean Square
LRUT	Long Range Ultrasonic Testing
MEMS	Micro Electro Mechanical Systems
MESC	Modal Strain Energy Change
MSECR	Modal Strain Energy Change Ratio
MPN	Monitoring Priority Number
MSE	Modal Strain Energy
NASA	National Aeronautics and Space Administration
NCS	Norwegian Continental Shelf
NDT	Non Destructive Testing
OLM	On Line Monitoring

OTC	Offshore Technology Conference
PDO	Plan for Development and Operation
PGN	Prognosis Confidence
PIO	Plan for Installation and Operation
PZT	Lead Zirconate Titanate
RBI	Risk Based Inspection
ROV	Remotely Operated Vehicle
RSF	Residual Strength Factor
SCC	Stress Corrosion Cracking
SCF	Stress Concentration Factor
SEV	Severity of Failure
SHM	Structural Health Monitoring
SLS	Serviceability Limit State
SR	Structural Redundancy
STFT	Short-Time Fourier Transform
SVD	Singular Value Decomposition
TF	Transmissibility Function
TLP	Tension Leg Platform
ULS	Ultimate Limit State
UM	Usage Monitoring
UT	Ultrasonic Testing
WSN	Wireless Sensing Network
WT	Wavelet Transform

1. INTRODUCTION

1.1 BACKGROUND

An increasing number of jacket platforms are passing their assigned lifetime both on the Norwegian continental shelf (NCS) and other parts of the world. According to the Norwegian petroleum report of 2013, the average age of the jacket platforms on NCS is approximately 24 years [1]. Assigned lifetime for a jacket is not an exact age, but the mean age can approximately be estimated to be 30 years. The reasons for extending the lifetime of platforms is due to factors like cost savings, increased use of subsea tiebacks and technology advancements. Such technology advancements are for example within extended reach drilling. This has led to an increased importance of life extension and evaluation of the structural integrity. SHM can be considered as a tool for evaluating structural integrity and remaining lifetime. SHM is defined as the process of implementing a damage detection strategy for aerospace, civil and mechanical engineering [2]. Implementing SHM may cause an increase in procurement and installation cost, but it may in the long term result in a decrease in operational costs and maintenance. Therefore there has been great attention to the field of SHM in the last decades. This includes improvements in the sensor robustness, accuracy, efficiency and lower cost. In addition to evaluating the structural integrity, SHM can be a tool to optimize design criteria of future structures by calibrating todays design coefficients based on real historical data.

95% of the offshore platforms in the world are of steel jacket design [3]. Jacket structures are robust platforms used mainly in shallow waters due to its rigid dynamic characteristics. Shallow waters are defined as water depth of less than 300 meters. The jacket is a construction consisting of steel tubes anchored to the seabed with the use of piles. Figure 1-1 is showing a typical jacket platform above sea surface, with visible tubular joints in the air gap [4]. The jacket is in general designed to withstand parameters as weight of topside, impact loads, wind loads, loads from current, corrosion and fatigue. Exposure of these parameters during a design lifetime will affect the structural integrity of the structure. To ensure safe use, prevent failures and control further degradation SHM may an important tool.

FIGURE 1-1: OFFSHORE JACKET

1.2 Aim of the Thesis

The aim of what is reported is to explore how developments within SHM can be applied as a tool for assessing the structural integrity of offshore jackets. More specifically develop a proposal for monitoring an existing jacket in cost-effective manner.

1.3 The Scope of Work

The scope is to evaluate current technologies in the field of SHM, consider new research and propose a methodology to create a monitoring plan for offshore jackets. The thesis includes a case study of a fictional platform on the NCS, where a proposal for an appropriate cost-effective monitoring plan is developed. The main objectives, as defined by DNV GL are as follows:

- Perform a literature study on current knowledge of SHM of offshore structures with emphasis on jackets.
- Study methodologies described in current knowledge, including planning of monitoring setups, data collection, data analysis and evaluation of structural integrity.
- Describe typical failure modes.
- Identify which parameters should be included in the monitoring system.
- Propose suitable sensors for detecting the key parameters (identified in the bullet item above).
- Evaluate the maturity of various sensors and measurement techniques.
- Explore data processing methodologies and evaluate their suitability.
- Develop a proposal for monitoring of an existing jacket in a cost-effective manner.

1.4 Limitations

The thesis is limited by the following considerations:

- Only considering the design of jacket structures (no topside consideration).
- Evaluation of sensors assessing structural integrity only.

1.5 Organization of the Thesis

Following this introduction the report is divided into 6 Chapters. Chapter 2 presents a literature survey of existing knowledge in the field of SHM in general. In addition fundamental definitions are explained. Underlying knowledge about design concept, damage parameters and failure modes of the offshore jacket structure are then explained in Chapter 3. A literature survey of the development of SHM within jacket structures is presented in Chapter 4. In Chapter 5, a proposed methodology based on the obtained knowledge from Chapter 2, 3 and 4 is presented and explained. Further, a case study of a fictional platform on the NCS was performed in Chapter 6, testing the methodology developed in Chapter 5. In Chapter 7, conclusive remarks about the knowledge obtained in the thesis is presented in addition to recommendations for further work.

2. LITERATURE SURVEY OF SHM IN GENERAL

2.1 SHM METHOD

The following definitions are based on a review of SHM literature done by Los Alamos national laboratory in 2001 [2]. SHM is defined as the process of implementing a damage detection strategy for aerospace, civil and mechanical engineering. Usage monitoring (UM) is a measure of the inputs and responses of a structure before damage occurs. UM is done so that regression analysis can be performed, estimating the relationship between different parameters. Further, the analysis can be used to predict the damage and deterioration in structural condition. Prognosis is defined as the coupling of information from SHM, UM, current environmental and operational conditions, previous component and system level testing, and numerical modelling to estimate the remaining useful life of the system.

SHM involves observation of a structure by the use of sensors. For instance, measurement of the dynamic characteristics of a structure can be done. The evaluation of this data with the use of post processing and damage evaluation models results in an evaluation of the structural integrity of the structure. Also, permanently mounted sensors detecting local damage at the specific point of installation is possible to combine with the former mentioned technique. SHM differ from NDT techniques due to the use of sensors that are permanently mounted on the object of interest and reports continuously or periodic as an online monitoring system.

Condition monitoring (CM) is another term not to confuse with SHM. CM is the implementation of a measurement system for machinery during operation [5]. This means that CM contains similarities to SHM. In fact in Section 5.2 the use of a monitoring priority number (MPN) which is used in CM was evaluated. It is important to be aware of that in the NORSOK standards; “condition monitoring” is defined as “*a systematic examination and evaluation of the overall structural condition ensuring that an acceptable level of structural integrity and safety is maintained”.* In other words, condition monitoring has at least two definitions. In the following, CM is defined as a measurement system for machinery during operation.

In Figure 2-1, the SHM method is broken down in all its significant elements [6]. There are four different phases. This can be seen as an iterative process where all the phases are equally relaying on each other. Section 2.1.1 elaborates on the different SHM steps.

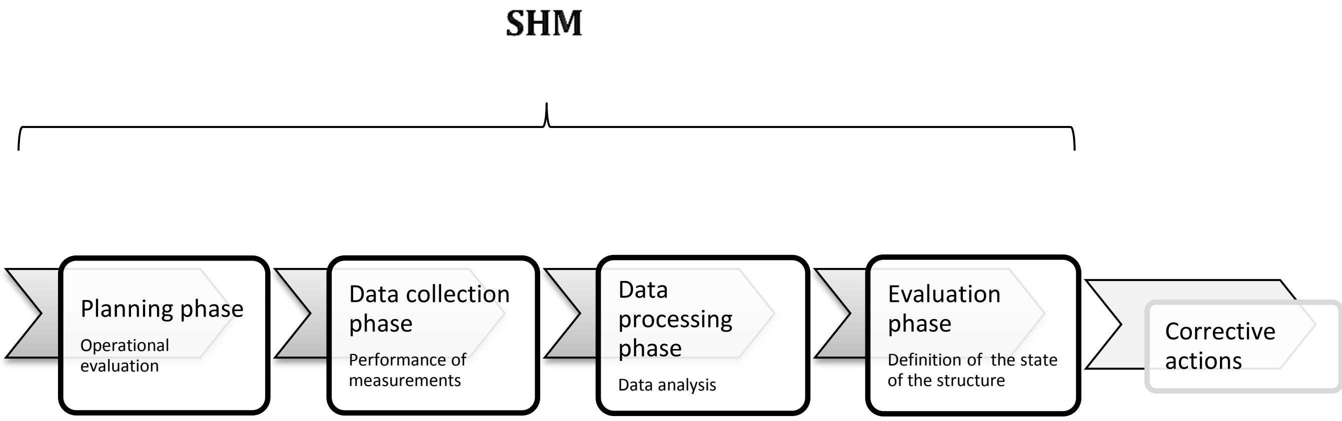


FIGURE 2-1: SHM PHASES

2.1.1 SHM PHASES

Planning Phase

The planning phase is where the scope of all the SHM phases is to be defined. The following questions are of major importance in that regard:

- When do we need to monitor?
- Why do we want to monitor?
- What do we want to monitor?
- How do we want to monitor?

This means that it is important to obtain knowledge about the motive and when monitoring needs to be done. In addition failure modes and monitoring techniques need to be established. Motives for installing a SHM system is mainly related to reduced cost and risk. Reduced cost can be a result of the fact that there is no need to use divers or remote operating vehicles (ROV) when the SHM system is operational. British Petroleum has stated that they saved cost equal to approximately £50 million on one of their offshore platforms [2]. By neglecting the use of divers the risk of human lives will reduce drastically as well. To uncover what is most important to monitor, identification of critical failure modes needs to be performed. For instance, if fatigue cracks are the most important failure mode, identification of measurement location can be done by analysis of the connections with large stress variations.

Data Collection phase

Data collection phase is the actual monitoring process. First, measurement technique and sensor selection needs to be done. This is followed by identification of specific sensor locations and evaluation of the amount of sensors needed. Sampling frequency and sampling period are governing factors for data storage capacity and processing methods. If the sampling frequency is high, the amount of data to be processed and stored will increase. Also a consideration needs to be done, evaluating if the measurement needs to be continuous or be done in periods. Periodic measuring will decrease the amount of data that needs to be processed and stored, however continuous measuring is sometimes needed. An example of this is if the aim of the SHM deployment is to measure fatigue crack growth. In this situation it may be necessary to monitor continuously to detect changes in the structural characteristics. Also data acquisition facilities need to be planned and installed. Data normalization is a term used during data collection. The process of normalizing the data means to separate the monitored signal changes caused by operational and environmental variations. This is done so that environmental variations not can be evaluated as a source of damage.

Data Processing phase

Data processing involves using the collected data and to transform this to data that is possible to understand and evaluate. Several transformations are used, but the most used transformations are based on a method called Fourier Transform (FT). The purpose of these methods is basically to transform a data signal retrieved from sensors from time domain to frequency domain. SHM involves a vast amount of data, but not all data is valuable for the structural assessment. Therefore the challenge with data processing is to utilize the most important data. The task of identifying the damage indicator which is sensitive to damage from the vibration response is needed. This is called system identification.

Evaluation of Processed Data

The last step is defining the state of the structure by comparing the evaluated data from the data processing phase to acceptance criteria. Numerical models may be used to identify and quantify the damage. The methods for damage identification can be classified in four levels[7].

Level 1: Determination that damage is present in the structure

Level 2: Level 1 plus determination of the geometric location of the damage

Level 3: Level 2 plus quantification of the severity of the damage

Level 4: Level 3 plus prediction of the remaining service life of the structure

2.1.2 Disciplines Implemented in a SHM System

SHM is a system covering a substantial number of disciplines. Technology within sensing, power, communication, storage, signal processing and evaluation algorithms is the fundamentals behind a SHM system [8]. This makes the understanding of SHM systems to be a challenging task. Subsequently, being dependent on many types of technologies should be regarded as an advantage. There have been major developments within these disciplines during the last two decades. A reason for this is the increased focus on research and reduced cost of technology. Figure 2-2 illustrates the disciplines and how they are correlated in the SHM system [8].

The evolution seen in the cell phone market is a good example of the rapid technology advancements. In the last twenty years, a cell phone has evolved from just being a phone to being a smart phone with new technology. State of the art batteries, storage capabilities and micro-processors are just some of the technologies an average phone includes today. In this thesis, examples of how the SHM systems are directly influenced by the technology advancements seen the last decades are given.

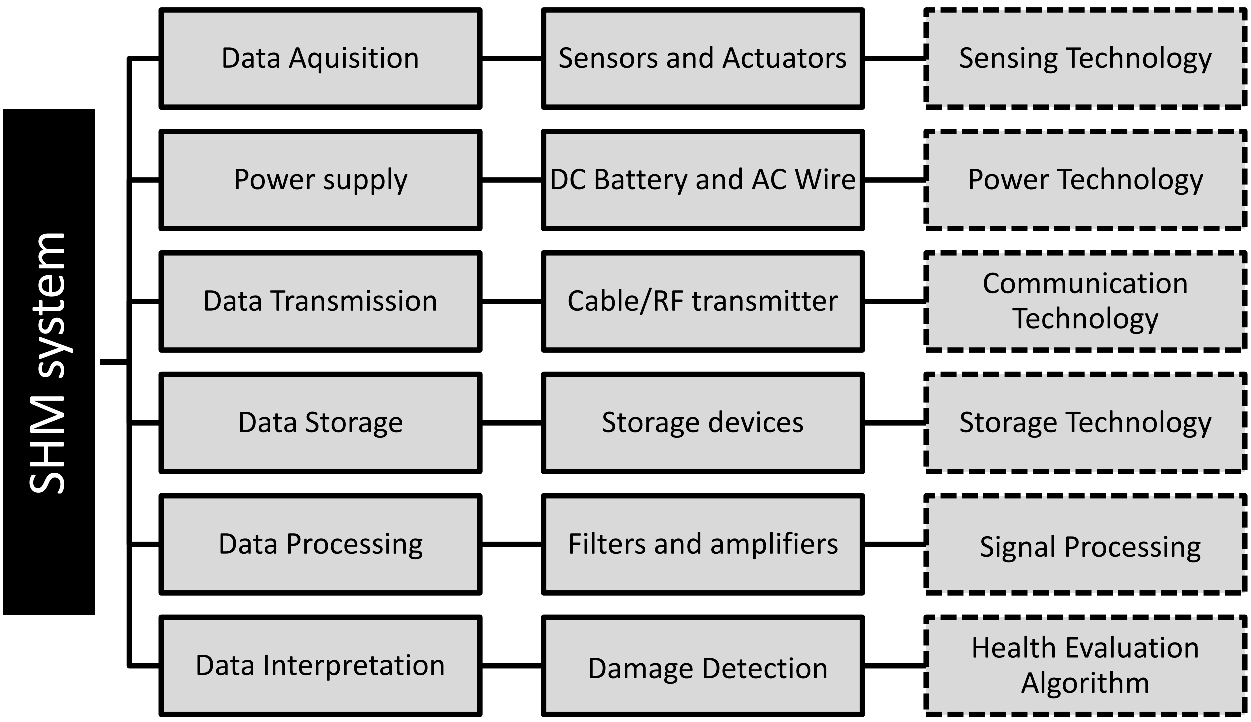


Figure 2-2: SHM disciplines

2.2 Important Definitions in the SHM Methodology

2.2.1 Local Damage Detection Techniques

Structural damage found by typical NDT techniques like visual, acoustic, magnetic field, strain measurement, eddy current etc., are categorized as local damage techniques. Local damage techniques are restricted to detect damage at the point the sensor is installed. These techniques are in some degree effective, but are restricted to find only local damage on the elements inspected. In addition, the examined element needs to be highly accessible. Since these sensors only detect damage at their position, the concentration of sensors or manual inspection points need to be high. This makes it a costly and time consuming technique. The positive aspect is that the damage is localized when it's first detected compared to the global damage measuring technique which needs further analysis to localize any damage [7]. This is the most used measuring technique in the offshore industry today.

2.2.2 Global Damage Detection Techniques

Global damage detection techniques aim to measure damage by global techniques. Today the most dominant global damage detection technique is vibration based damage detection. This technique uses the difference in dynamic characteristics between an initial state (baseline) and experimental results to detect, quantify or/and localize damage. Dynamic characteristics can for instance be modal frequencies and mode shapes. These characteristics can give information of mass, flexibility and damping of the structure. Initial assumptions can be obtained from early testing from the time the structure is in an undamaged condition or this can be calculated in a FE-model. The experimental results are obtained from accelerometers placed on the structure and the structure is excited by either measurable excitation or natural excitation. The latter excitation method is called ambient excitation. In contrast with the local measuring techniques, the vibration based damage detection is not able to quantify and localize small damage in an effective manner [9]. A thorough summary review of vibration based damage detection methods were done in 1998 at the Los Alamos National Laboratory [10]. Here problems, methods and recommendations for future work were explained. According to this paper global damage are divided into two, linear or nonlinear. Linear damage is defined as when an initially linear-elastic structure remains linear-elastic after damage. In these situations the change in dynamic characteristics are due to material or geometry changes and the structural response can be calculated by using linear equations of motion. Most of the methods in SHM are based on linear damage based on reduction in stiffness. Nonlinear damage is occurring when an initially linear elastic structure is behaving nonlinear after damage. Opening and closing of fatigue cracks are examples of nonlinear damage. Linear vibration based damage detection can also be divided further into two types: parametric and non-parametric. Where the former is model based and the latter is non-model based.

The four levels of damage identification explained in Section 2.1.1 are used to describe the extent of damage identification for the different global damage detection methodologies. It is also the basis for the definition of two other terms in the global damage measuring methodology. They are the forward problem and backward problem. The forward problem being the method of detecting damage by the use of a damage indicator, and is mainly related to level 1. The reverse problem is the method of evaluating damage severity and location of the damage. Hence, this is related to level 2 and 3. Level 4 is mainly related to fracture mechanics (FM), calculating the remaining life time based on crack propagation [10].

Historically it seems that the biggest challenge for the vibration based damage detection has been to find the most adequate damage indicator. Several damage indicators are proposed, and the ones mainly found in literature are natural frequencies, mode shapes, change in compliance and modal strain energy change. Those methods among others have been demonstrated in Section 4.4.

2.2.3 Active and Passive Sensing

Active sensing is defined as measurements done by transmitting energy. On the other hand, passive sensing is defined as measurements done with only natural source of energy [11]. The easiest way of explaining the two sensing methods are to use a simple example. A camera with a flash can be seen as an active sensor. The lens uses the reflecting energy from the flash to make up an image. On the other hand, a camera without a flash uses naturally emitted light to make up the same image and therefore is categorized as a passive sensor.

The most important difference between these two sensing technologies is that active sensing demands a considerable amount of energy compared to passive sensing. This means that if the measurement system relies on batteries, the passive sensors would be preferable. With that being said, the passive sensing relies on receiving natural sources of energy which is a considerable drawback since this potentially results in collected data with a considerable amount of noise.

2.3 Development of SHM in Different Industries

There have been significant advancements of SHM systems in many industries until today. SHM of offshore jackets is not a new field, but have experienced a renaissance in the last two decades. Therefore exploring the SHM methodology advancements of other industries are of importance. In this section, the development within civil engineering with emphasis on bridge monitoring and the development within aerospace systems are examined. The reason for this is that bridge monitoring use testing techniques with relevance to those techniques used on offshore structures. Also the aerospace industry is examined due to their leading position in SHM throughout history.

2.3.1 CIVIL ENGINEERING

Within the civil engineering community, there have been significant developments of SHM since the 80's [12]. In the past several decades there have been many fatale highway bridge collapses e.g. Silver Bridge over the Ohio River (1967), Mianus River Bridge (1983) and Minneapolis Highway Bridge (2007). These accidents have been important factors for focusing on the structural integrity of the rapidly aging bridges around the world. There is a huge amount of available information about bridge monitoring. With relevance to monitoring of offshore structures, it is the global monitoring techniques that are of importance. Even though the offshore industry started experimenting with vibration based damage detection early, it seems like the civil engineering community have been experiencing significant advancements in this field non-stop since the beginning in the 80's.

As explained in Section 2.2.2, vibration based damage detection is a technique used to measure the dynamic characteristics of a structure [13]. This is preferably done when the excitation (input) and the movement (output) is measurable. Due to constant traffic, it is not possible to measure the excitation on bridges in service. Most of the methods uses accelerometers which register the dynamic movement of a bridge structure without artificial loading (unknown input), also called ambient loading. In this way it is possible to find the modes of the structure, and compare the measured dynamic characteristics with earlier measurements from when the bridge was new or with a FE-model. A study was done by Farrar and Jauregi in 1996 comparing vibration based damage detection methods on the I-40 Bridge in USA [14]. In Section 4.4, an example of how methods such as the compliance change can be used on offshore structures is investigated.

Even though global damage techniques such as vibration based damage detection are most commonly used in civil structures, it is important to note that in the civil engineering community this type of monitoring is frequently used in combination with regular inspections using NDT techniques. Strain measurements, temperature measurement and acoustic emission monitoring are some of the main NDT techniques used in bridge monitoring [15].

It is observed through literature that long term monitoring of bridges with wireless sensing networks (WSN) have been used increasingly during the last years due to the development in sensing, communication and data systems. Figure 2-3 show all types of measurements that are possible to do on a bridge, and with the development within WSN, it is likely that many large bridges in the future will have instruments for all these types of measurements [16].

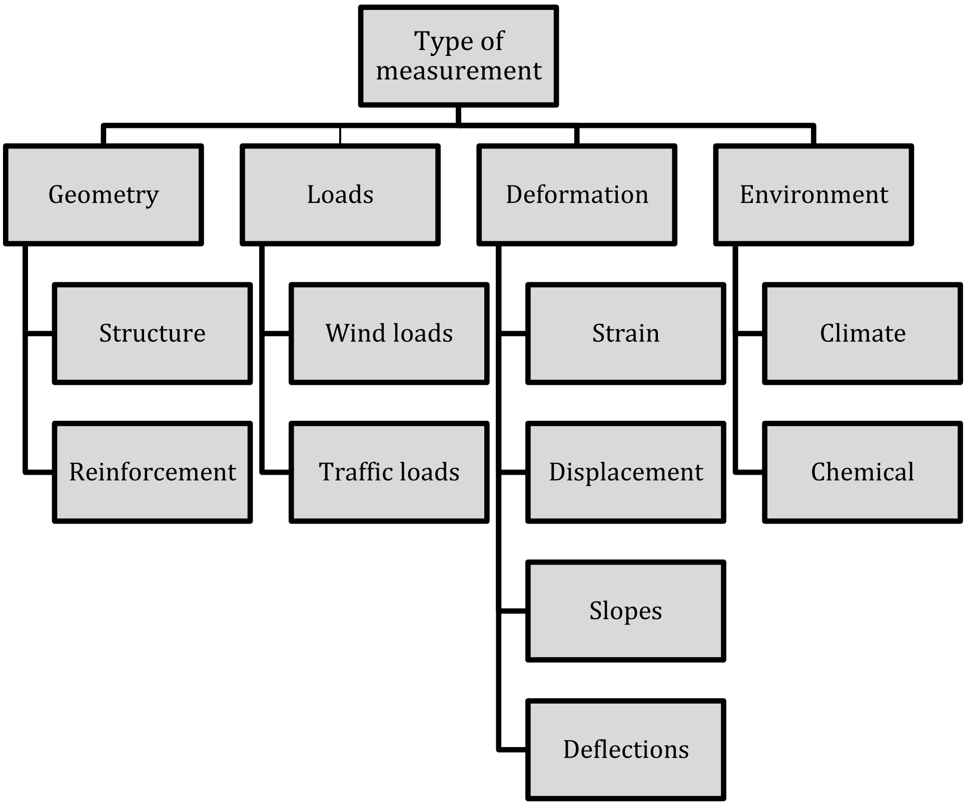


FIGURE 2-3: MEASUREMENT ON BRIDGES

2.3.2 AEROSPACE INDUSTRY

An aircraft can be subjected to severe consequence if something goes wrong with a critical component. For that reason, the aerospace industry has been a cutting edge industry in the field of SHM. In addition to the catastrophic consequence of a potential damage, the aircraft is an object suffering from frequent fatigue loading during take-off, in-air service, and landing. In addition it is exposed to a highly corrosive environment [6]. Fatigue loading and corrosive environment are also what offshore structures frequently are exposed to.

In 1954, the industry faced a game changing incident with the loss of 3 De Havilland Comet aircrafts in a short period of time due to crack propagation [17]. This helped the industry focus on fatigue damage in conjunction with pressurized cabins, simultaneously as fracture mechanics theories were being applied and proved helpful. An integrated maintenance system was developed for the Boeing 757/767 already in the 1980’s, taking a lead in the use of integrated on-board systems [12].

Historically, the assessment of damage on aircrafts were based on number of flight hours, but with the development of fatigue and load cycle counting methods, it was possible to relate load cycles with structural damage [18]. In these days, most aircrafts are equipped with an integrated vehicle health management system (IVHM) recording hundreds of parameters and feed the information to the on-board aircraft computer. An IVHM system should include automatic detection, diagnosis, prognosis and mitigation of unwanted events due to a component failure. Figure 2-4 illustrates how General Electric's IVHM system looks like in general [19]. The system *collects* real-time data from sensors equipped on the aircraft, and these sensors are part of a WSN *connected* to a central for data processing and *detection* of damage. That information will thereafter be *directed* to the right department where mitigating measures and maintenance will be executed.

Even though the use of IVHM is highly available and the majority of aircrafts today are equipped with this system, the system is not reliable enough to avoid regular periodic inspection. The currently used NDT techniques in the aerospace industry are visual inspections followed by eddy current, ultrasonic, X-ray etc. The second generation reusable launch vehicle currently under development at the National Aeronautics and Space Administration (NASA) is using a modified IVHM system [20]. This modified system will emphasize on rapid damage recognition so that it is possible to do quicker corrective actions. NASA is stating that this system likely will, among other things, include smart sensors as micro electro mechanical systems (MEMS), diagnostic and prognostics software for sensors and components, model based reasoning systems for subsystem and system level managers, advanced on-board and ground-based mission and maintenance planners [20]. If history repeats itself, the aircraft manufacturers will use the same systems in some years, as development proceeds.

Figure 2-4: Integrated Vehicle Health Monitoring

2.3.3 Discussion

In the civil engineering industry, vibration based damage detection is a frequently used monitoring technique. In Section 4.4 some of the methods developed for civil engineering is discussed. Numerous papers are written about bridge monitoring using the combination of vibration based damage detection and WSN. In this area, the offshore industry has potential to learn from the civil engineering community. The challenge of offshore structure monitoring is the rough environment and this may be one reason why especially the WSN is not yet fully developed for offshore platforms.

The aerospace industry is in the front of integrated SHM systems. The advancement in integrated intelligent monitoring technology on space crafts and aircrafts are of importance also for other industries. There is a trend of making intelligent monitoring systems implementing MEMS on structures as well, and this is trending from the aircraft industry.

3. OFFSHORE JACKET PLATFORM

This chapter contains an overview of the governing standards and recommendations for design of offshore jacket structures. This is followed by information about concept selection of offshore structures and essential information about the design of jackets. In the last section, the damage parameters and failure modes of jackets are investigated and accounted for.

3.1 AVAILABLE CODES AND STANDARDS

The governing hierarchy pyramid in Norway is as illustrated in Figure 3-1. The Petroleum Safety Authority (PSA) is on top of the hierarchy. This is followed by industry standards which are giving guidelines on how to fulfil the requirements of the PSA. ISO standards are general international standards, whilst NORSOK are guidelines developed specifically for offshore structures on the NCS. On the bottom of the hierarchy are the recommended practices and company procedures containing proposals for how to interpret the standards.

Table 3-1 lists the standards containing design procedures and assessment of structural integrity of jacket structures. The NORSOK standards are used in this thesis as compliment to the ISO standards in addition to recommended practice from DNV GL.

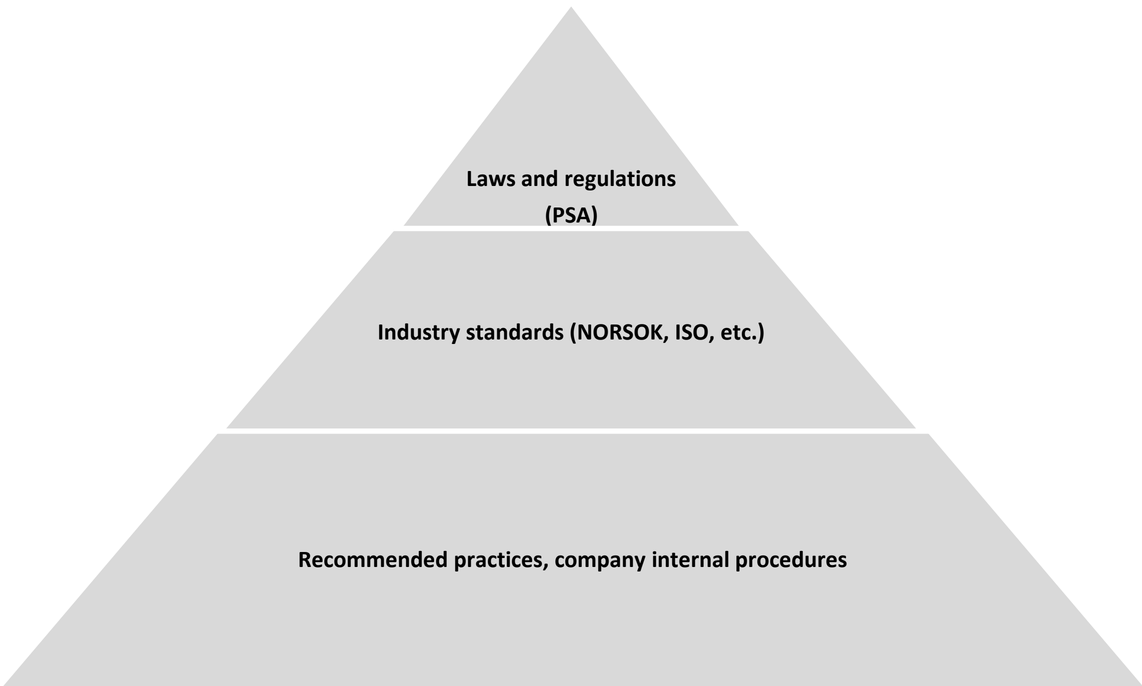


FIGURE 3-1: GOVERNING HIERARCHY

TABLE 3-1: ISO, NORSOK AND RP'S

Standard	Title	Content
ISO 19902 [21]	Petroleum and natural gas industries — Fixed steel offshore structures	Requirements and recommendations for design of fixed steel offshore structures
NORSOK N-001 [22]	Integrity of Offshore Structures	Information of the integrity of offshore structures
NORSOK N-003 [23]	Actions and Actions Effects	Information about principals and guidelines for determination of action affects for the structural design of offshore structures
NORSOK N-004 [24]	Design of Steel Structures	Information of the guidelines and requirements for design and documentation of offshore steel structures
NORSOK M-101 [25]	Structural Steel Fabrication	Requirements for fabrication and inspection of offshore steel structures
DNVGL RP-C203 [26]	Fatigue Design of Offshore Steel Structures	Recommendations for fatigue design based on fatigue tests and fracture mechanics

3.2 JACKET DESIGN CONCEPT

The petroleum industry has invented several innovative structures mainly due to the challenges related to deep water. It is common practice to divide the offshore structures into two categories, namely floating and bottom-supported structures. Bottom supported structures include roughly jackets, jack-ups and compliant towers, while the floating structures include semi-submersibles, tension leg platforms (TLP's), spars and floating production, storage and offloading units (FPSO's). The concept selection is dependent on several parameters such as; reservoir size, water depth and type of well [27].

Table 3-2 lists the most important differences between the two main offshore structures categories [28]. With regards to SHM, the major difference between the two concepts is that bottom supported structures are permanently installed at the production location (except from the jack-up). This means that there are locations on bottom supported structures which never can be subjected to manual inspection after installation. The foundation (e.g. piles) is an example of such a place. In contrast, floating structures can be towed to shore for thorough maintenance if needed.

TABLE 3-2: BOTTOM FOUNDED VS. FLOATING STRUCTURES

Function	Bottom-Supported	Floating
Payload support	Gravity based with foundation	Buoyancy
Well access	"Rigid" conductors, dry wellhead tree	"Dynamic" risers, wet wellhead tree
Environmental loads	Resisted by strength of structure and foundation, compliant structure inertia	Resisted by vessel inertia and stability, mooring strength
Construction	Tubular space frame: fabrication yards	Plate frame displacement hull: ship yards
Installation	Barge (dry) transport and launch, piled foundations	Wet or dry transport, towing to site and attachment to pre-installed moorings
Regulatory and design practices	Oil industry practices and government petroleum regulations	Oil industry practices, government petroleum regulations and Coast Guard & International Maritime regulations

Jacket structures are highly proven structural technology. Usually the platforms are fabricated onshore and installed offshore by the use of cranes or launch from a barge. Thereafter the topside is installed by a crane ship, placing the topside upon the jacket structure at the installation site. The jacket consists of tubular elements making up a structurally rigid framework, making it suitable for long time production. The different types of frameworks are illustrated in Figure 3-2 [29]. The frameworks consist mainly of 3 different joints:

- X
- Y
- K

Figure 3-3 from ISO 19902 [21] is an illustration of the different types of joints and the force distribution ratio. The main important difference of these joints with regards to analysis is that they distribute the axial force in a different manner.

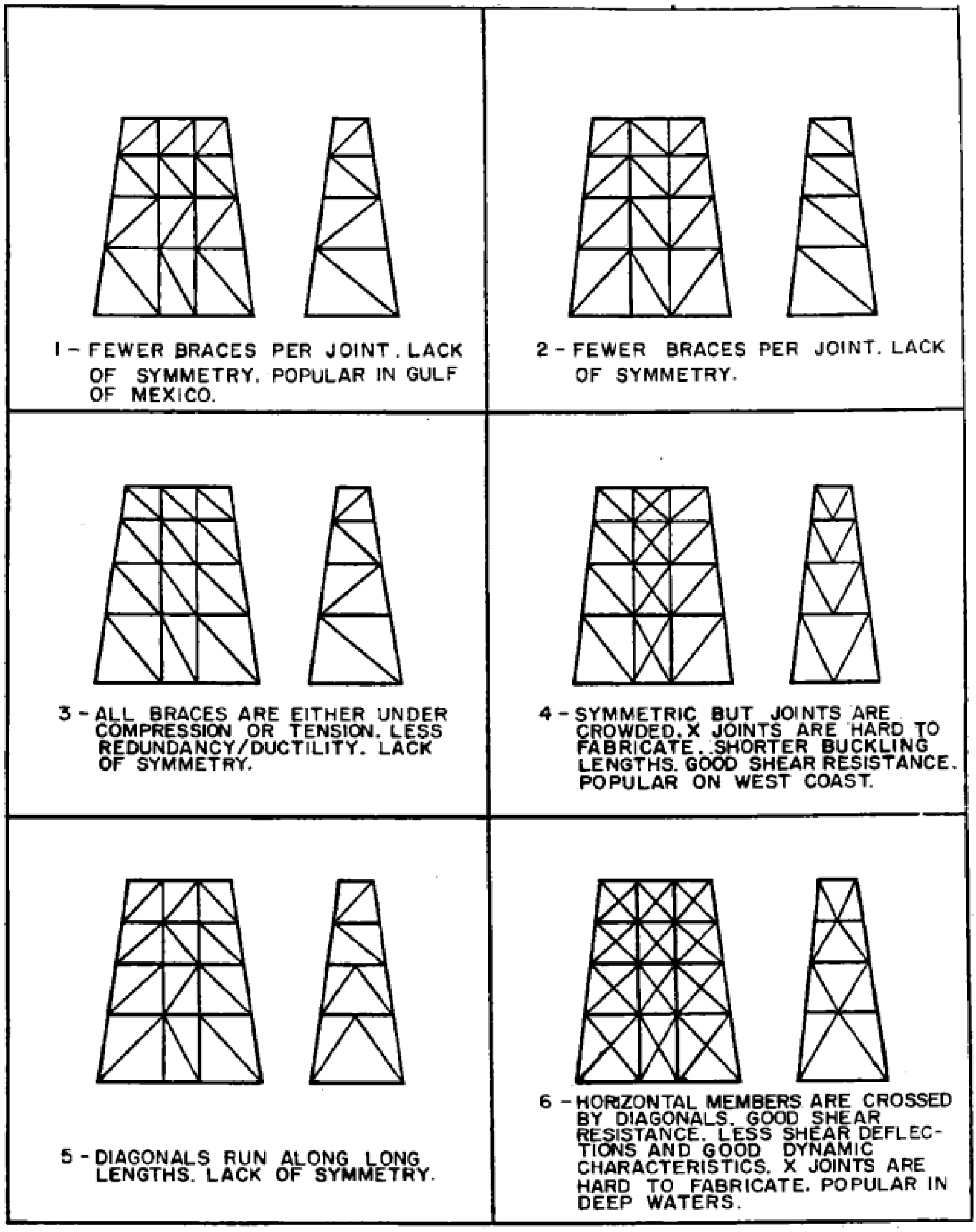


FIGURE 3-2: BRACING PATTERNS OF A JACKET

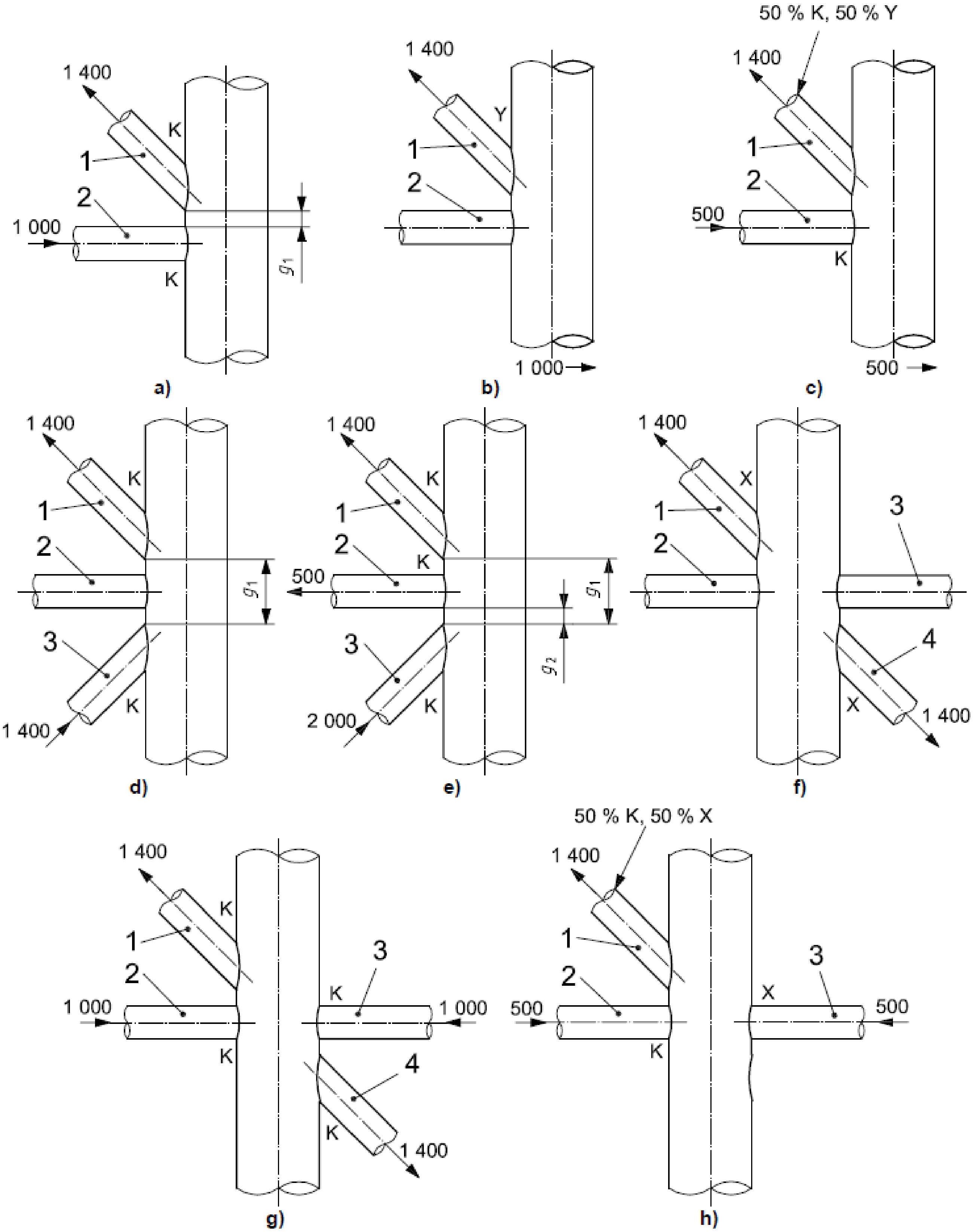


Figure 3-3: Types of joints

Offshore jackets are installed with piles on each leg connected to the seabed for safe foundation and satisfying stability. The piles take up axial force (both tension and compression) and also lateral loads acting perpendicular to the piles [27]. The main types of piles are:

- Main and skirt pile configuration
  Piles are inserted in the legs of the platform (main pile) and through each skirt pile.
- Clustered pile configuration
  Piles are inserted in the seabed around the main legs in pile clusters.

Bucket foundation is an alternative to the pile method. The jacket legs are placed in large inverted buckets which are penetrated to the seabed.

The jacket concept is normally used in shallow waters with a water depth less than 300 m. The reason for this is mainly for avoiding resonance between the structure and the periodic wave loads. The jacket will experience bending in the horizontal plane [27]. This problem is described in Figure 3-4 were the natural period for the main offshore structures are placed in the same diagram as the wave spectrum for different significant wave heights (H_S) [27]. Since the jacket structure is rigid, the natural period is low. The platform third from the left is a compliant tower which is a concept similar to a jacket structure. However, the compliant tower has reduced rigid properties resulting in an increase of the natural period. Equation for the natural period for a fixed steel structure in surge/sway is shown below [27].

$$T_0 = 2\pi\sqrt{\frac{m}{k}} \tag{3.1}$$

Where the stiffness can be expressed as:

$$k = \frac{F}{x} = \frac{3EI}{h^3} \tag{3.2}$$

Here, F is the restoring force corresponding to the displacement x. E is the Young's modulus, I is the moment of inertia and h is the height of the jacket structure.

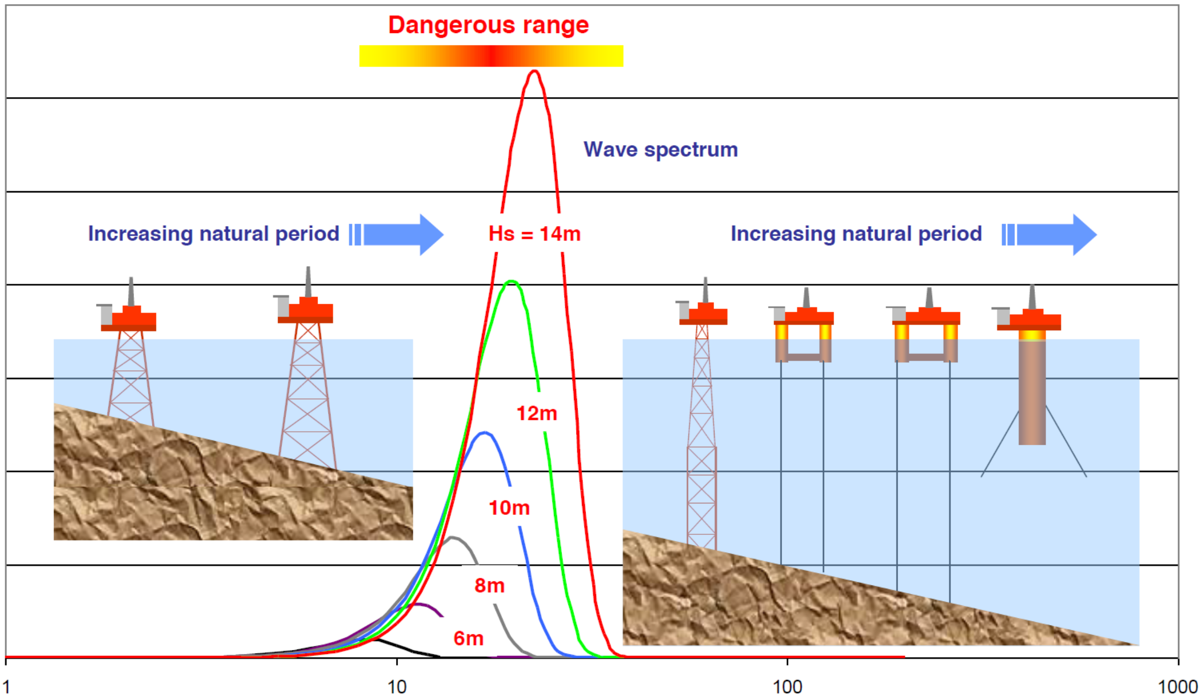


Figure 3-4: Wave spectrum vs. concept collection

3.3 Damage Parameters and Failure Modes of an Offshore Jacket Platform

Jacket structures are in general designed according to ISO 19902 [21]. The platforms placed on the NCS can be designed according to NORSOK N-004 [24]. A jacket is designed according to four limit states; ultimate limit state (ULS), fatigue limit state (FLS), accidental limit state (ALS) and serviceability limit state (SLS). The limit states are explained in Table 3-3 below [30]:

Table 3-3: Limit States

Limit State	Definition
ULS	Ultimate resistance for carrying loads
FLS	Possibility of failure due to cyclic loading
ALS	Failure due to an accidental event or operational failure
SLS	Criteria applicable to normal use or durability

SHM is related to evaluation of structural integrity and to predict remaining service life. For that reason evaluation of SLS and ALS is not relevant. SLS includes damages that won't have any important impact on the integrity of the structure and ALS is scenarios which is hard to predict and uncontrollable. The important thing in this context is to compare the measurements to ULS and FLS criteria. Also by using measurements as a tool to prove conservativism in the industry with regards to design, standardized ULS and FLS design criteria can be changed [31].

Figure 3-5 is a graph showing the different damages that are reported on jacket structures on the NCS from 1974 until today [32]. The majority of the damages happened either on the nodes, braces or the jacket legs. In addition some few damages were related to the conductors and piles which in this thesis are regarded as a part of the jacket structure. As stated initially in Section 3.2, the piles are structural components that are unavailable for local monitoring.

The graph is based on numbers from the CODAM database made by the governing regulator on the NCS, PSA [32]. By looking at the damage distribution it is obvious that there are a majority of reported crack damages. According to the database, most of the incidents have not reported the cause of the crack damage. The fact that the cause is mostly unknown for these events leads to believe that fatigue may be the damage parameter. The reason for this is that fatigue is a result of exposed load cycles over time, and is not a result of a one-time event.

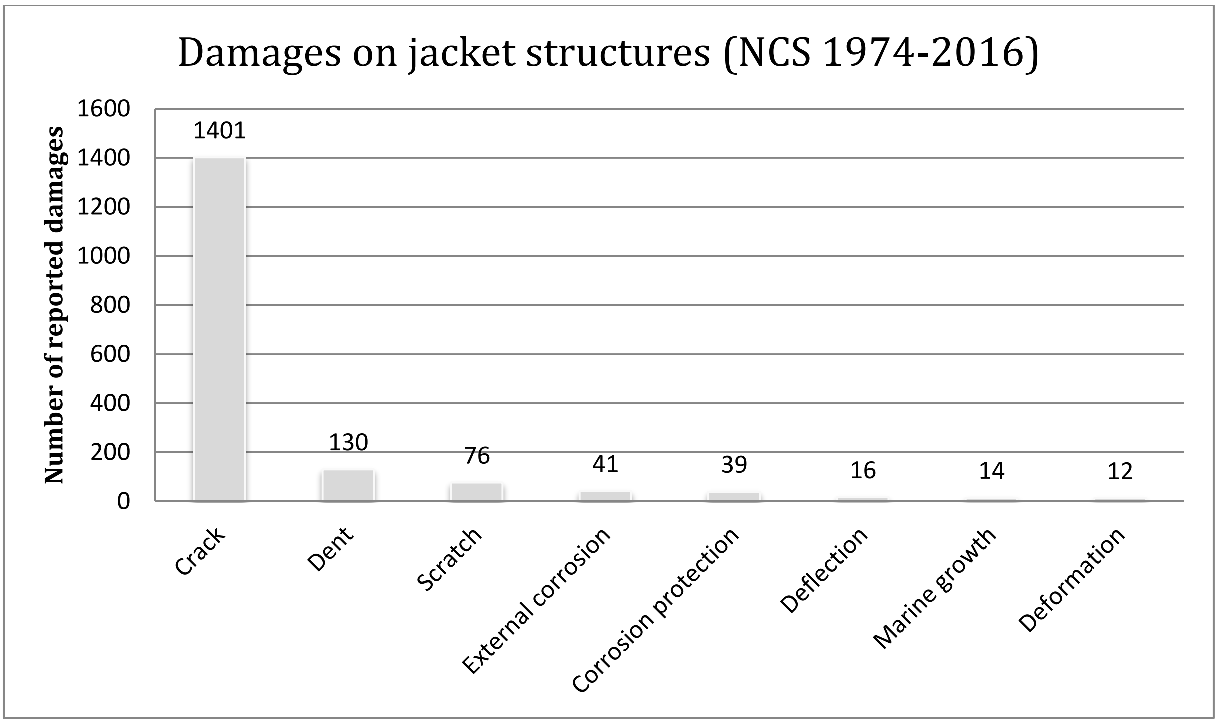


FIGURE 3-5: DAMAGES ON OFFSHORE JACKET STRUCTURES

The majority of the reported cracks were located on the nodes of the jacket structure. Also, almost all the damages on jacket legs seem to be related to cracks. The majority of the damages related to dents were reported on the bracings. The reason for that is mostly due the fact that the bracings are the structural elements vulnerable to denting by dropped objects. Deflection, external corrosion and scratches have been reported on all nodes, braces and legs. Marine growth and deformation is not reported on the nodes and deformation and corrosion protection is not reported on braces. These discoveries are summarized in Table 3-4.

TABLE 3-4: DAMAGE LOCATIONS

	Node	Brace	Leg	Conductor frame	Pile
Crack	✓	✓	✓	✓	
Dent		✓		✓	
Scratch	✓	✓	✓		
External corrosion	✓	✓	✓	✓	
Corrosion protection	✓		✓		✓
Deflection	✓	✓	✓		
Marine growth		✓	✓		
Deformation		✓	✓		

Figure 3-6 illustrate the annual distribution of reported incidents. Also here, the numbers are based on the CODAM data from PSA [32]. When adding up all the reported incidents from each year, the graph indicates that there was an increase in reported damages in the 1980's. The reason for this may be due to the increase of number of jacket structures on the NCS.

The data from the CODAM database results in some conclusions. It becomes quite clear that damages from cracks have been the most significant failure mode for offshore jacket structures throughout history. This results in believing that the cracks are first and foremost the failure mode which needs special attention and the damage parameter is most likely fatigue. Also, other damages as dents, scratches and corrosion are failure modes that need high consideration when designing and monitoring jacket structures.

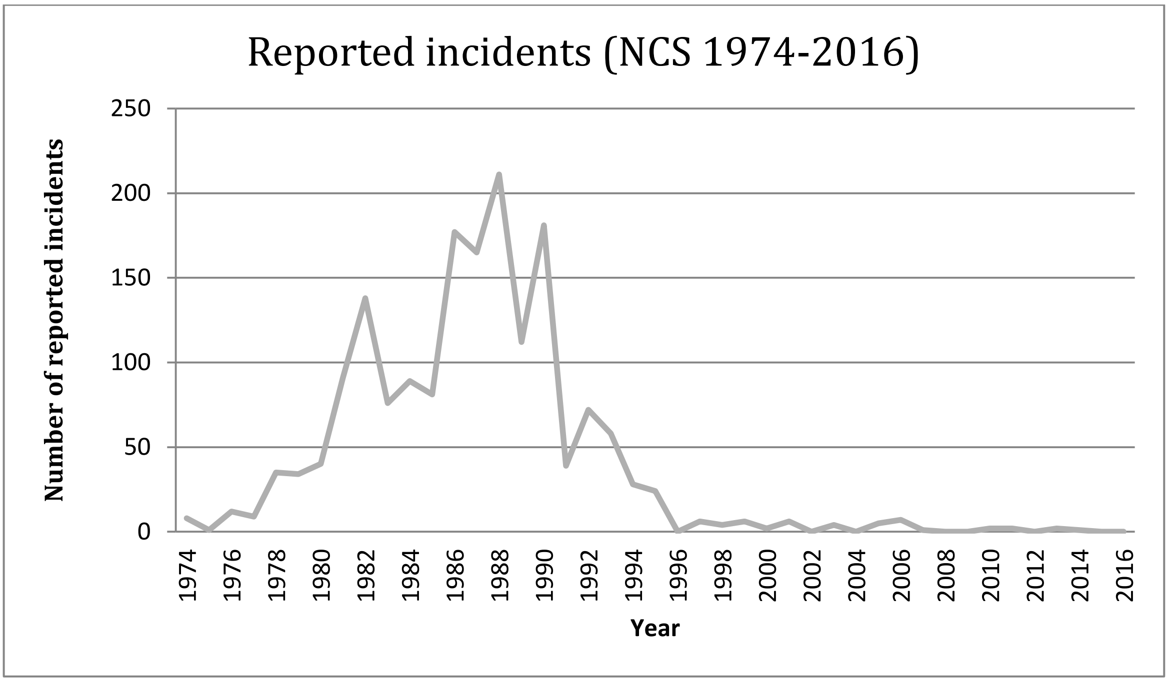


FIGURE 3-6: DISTRIBUTION OF REPORTED INCIDENTS

NORSOK N-005 lists damage parameters and failure modes that typically are occurring on jacket structures. The failure modes in NORSOK N-005 can be justified by looking at the statistics in Figure 3-5.

Typical damage parameters on an offshore jacket according to NORSOK N-005[33] are listed below:

- *Fatigue*
- *Corrosion*
- *Overloading (e.g. due to change of use)*
- *Accidental actions*
- *Other irregularities, such as marine fouling, scouring, etc.*

Typical failure modes on an offshore jacket according to NORSOK N-005[33] are listed below:

- *Joint degradation*
- *Corrosion damage*
- *Component failure*
- *Component damage*

In addition, ISO 19902 lists these failure modes for ULS [21]:

- *Tensile and compressive material yielding of a member's cross-section*
- *Buckling of a member and the post-buckling redistribution of internal forces that can involve local buckling (for open section this includes Euler and lateral torsional buckling)*
- *Local buckling*

A thorough investigation of the hazards developing these failure modes were done in a PhD. work by Gerhard Ersdal at The University of Stavanger [34]. Table 3-5 illustrates the hazards from this paper.

TABLE 3-5: HAZARDS OF AN OFFSHORE JACKET

Underlying cause	Source of hazard	Specific hazard
Insufficient strength	Gross error in design, fabrication, installation or operation	Insufficient design capacity Fabrication error Operational damage Modifications
	Degradation	Subsidence Corrosion Fatigue due to: - global cyclic loading - local cyclic loading - vortex induced vibrations - wave slam Widespread fatigue Scour Differential settlement
Excessive load	Environment	Global overload due to: - wave and current load - wave in deck load - wind load - unexpected marine growth - ice and snow loads - earthquake loads Local component overload due to: - wave and current load - wave in deck load - wave slam - vortex induced vibrations - wind load - unexpected marine growth - ice and snow loads - earthquake loads Worsening of wave climate
	Operation	Deck load – weight increase Unsecured objects – centre of gravity shift
	Accidental loads	Dropped objects Ship impact Explosion Fire & heat Aircraft impact Iceberg impact Submarine slide/Seabed slope instability

As seen in Table 3-5, the hazards are many and complex. The aim of a SHM system is to monitor the jacket so that the damage parameters and failure modes are detected before the structural integrity of the jacket structure is in danger. In the following the damage parameters from NORSOK N-005 affecting the jacket structure is described further.

3.3.1 FATIGUE

Fatigue damage is a result of reduction in strength of a material caused by cyclic loading. In an offshore environment, the cyclic loadings are mainly caused by waves and wind. The harsh and relatively consistent environment in the North Sea contributes to lots of cyclic loading compared to other oceans where there are offshore activities. In comparison, platforms in the Gulf of Mexico are exposed to a more inconsistent climate with mainly calm sea, but also hurricanes can occur. The aerospace industry has faced fatigue problems in a long period of time. In Section 2.4.2 there are given examples of how especially the crack propagation is an important bi-effect of fatigue loading. Also, the problems faced by the aerospace industry helped prove the fracture mechanics (FM) theories used also on offshore structures.

Offshore jackets are designed against fatigue damage, but uncertainties regarding the actual loading, environmental conditions and material properties make fatigue design a task filled with assumptions. Design fatigue factors (DFF) with values from 1-10 are added in the design phase to account for the uncertainty. A high DFF is given for remote areas where monitoring can be difficult to apply. In Table 3-6, the use of DFF is reproduced as it is seen in NORSOK N-001 [22].

TABLE 3-6: DESIGN FATIGUE FACTORS

Classification of structural components based on damage consequence	**Not accessible for inspection and repair or in the splash zone**	**Accessible for inspection, maintenance and repair, and where inspections or maintenance is planned**	
		Below splash zone	Above splash zone or internal
Substantial consequence	10	3	2
Without substantial consequence	3	2	1

According to DNVGL-RP-C203 [26], fatigue analysis during the design phase should be based on S-N data, which is determined by fatigue testing. Long term data of stress distribution is obtained by developing an expected stress history for the specific location of the platform. It is of major importance that this stress history is on the conservative side. However, the fatigue analysis can also be done based on fracture mechanics if the S-N data is not long enough for a critical component where a failure may lead to severe consequence [26].

Fatigue analysis based on S-N data takes use of the Miner's rule to establish fatigue life estimation. Here n_i is expected number of cycles and N_i is total amount of cycles:

$$D = \sum_{i=1}^{n} \frac{n_i}{N_i} \tag{3.3}$$

Fatigue analysis of jackets contains checks of all the locations where there is stress concentration. The places where the cracks often start are in riveted and welded connections [35]. On these places, the stress concentration factor (SCF) is high. SCF is defined as:

$$SCF = \frac{Hot\ Spot\ Stress}{Nominal\ Stress} \tag{3.4}$$

Hot spot stress and nominal stress is defined as the red and yellow region in Figure 3-7 below [26]. Hot spot stress is an increase of the nominal stress in a geographic restricted area around for instance a geometric detail. DNVGL-RP-C203 [26] includes guidelines for how to calculate these stresses by FE-modelling. This means that by calculating the SCF, it is possible to localize high criticality areas where a monitoring system should implement sensors able to detect fatigue cracks.

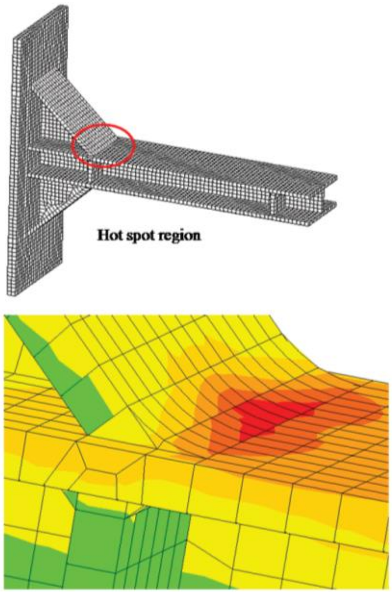


FIGURE 3-7: HOT SPOT AND NOMINAL STRESS

According to DNVGL-RP-C203 [26], fatigue analysis based on FM is recommended for use in assessment of acceptable defects, evaluation of acceptance criteria for fabrication and for planning in-service inspection. How the planning of in-service inspection intervals is being done is described in Section 4.1. By calculations, FM is a valuable tool to evaluate if a crack will exceed a crack size resulting in unstable fracture.

3.3.2 Corrosion

Corrosion damage in seawater is called aqueous corrosion and is a result of an electromechanical process between a cathode and an anode. These two elements are connected in a medium called electrolyte, and the electrons from the anode will move to the cathode. Figure 3-8 illustrates the electromechanical cell described.

The basic principle is that the iron in a metal will exhibit oxidation in reaction with an oxidant. In water, the equation will be like (3.5), the reactants will be iron, oxygen and water, and the products are hydrated iron (III) oxide and water [36]. The former product of the reaction is called rust and is what is observed on a corroded structural element.

$$4\,Fe + 3\,O_2 + 2\,H_2O \rightarrow 2\,Fe_2 0_3 *\ H_2O \qquad (3.5)$$

The corrosion process results in the material losing strength and the structure losing its integrity. For a material to corrode, oxygen and water need to be present. Therefore the most aggressive environment will be just above and below the sea surface on a jacket platform. The splash zone is thereby an exposed area with regards to corrosion. Pitting corrosion is the most common type of corrosion and is defined as localized corrosion leading to small holes in metals.

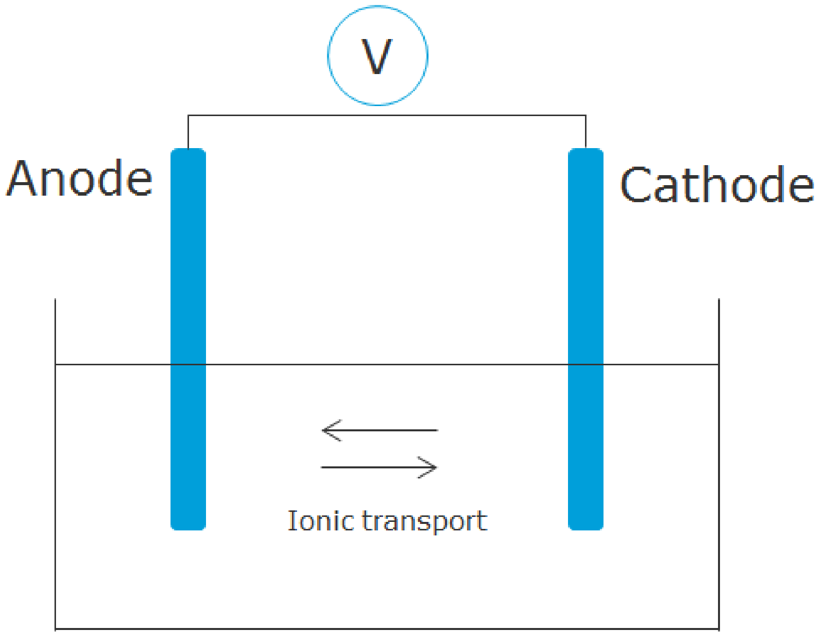


Figure 3-8: Electromechanical cell

In connection with corrosion, environmentally assisted cracking (EAC) is a term in the field of FM [17]. The EAC can be divided into four separate types:

- Stress corrosion cracking (SCC)
- Hydrogen embrittlement (HE)
- Corrosion fatigue (CF)
- Liquid metal embrittlement (LME)

SCC is a type of corrosion that is driven by an anodic reaction at the crack tip. There is crack propagation in this manner when the crack tip is consumed by the corrosion reaction. In other words, there need to be a substantially larger corrosion process in the crack tip than on other places on the crack, to develop this mechanism.

HE is a mechanism caused by the nature of the hydrogen atom. When large amount of hydrogen is present near an alloy, the hydrogen atom will (due to their small size) fit in interstitial sites in a metallic structure. This causes the bond strength between the metal atoms to be reduced and cracks can occur.

CF is defined as the acceleration of fatigue crack growth due to the combination of interaction with the environment and applied load [17]. This means that an element exposed to corrosion will develop cracks after shorter time and lower loads than usual. The CF mechanism can be accelerated due to cyclic load, time dependent load and/or a combination of both.

LME is a phenomenon which causes initially ductile metals to have brittle properties. Tensile stress is in most of the cases needed to have the ductile-brittle transformation. On the other hand it is discovered that aluminium in contact with liquid gallium, will make the aluminium brittle without any stress applied.

Prevention of corrosion is common on all offshore structures. It is common practice to use a sacrificial anode on the elements, which is a material that will corrode instead of the structural elements due to the electromechanical properties. The materials used for an anode are typically zink, aluminium or magnesium [37]. The use of these prevention techniques have reduced the risk of corrosion induced cracks in the offshore industry.

3.3.3 Overloading

Overloading of the structure can typically occur if there are changes at the topside loading arrangements. This can be due to new process facilities or other upgrades. Accidental actions can be scenarios like supply ship collision or other potential collisions from other structures offshore, e.g. floating living quarters.

3.3.4 OTHER IRREGULARITIES

Other irregularities, such as marine fouling and scouring can have unfortunate consequences for the integrity of the jacket structure. Marine fouling is the term used to describe marine growth on submerged material. This extensive layer on the jacket will increase the drag force on the legs due to increased friction and diameter of bracings, resulting in a higher load than intended from waves and current, according to Morison equation:

$$F = C_m \rho \frac{\pi}{4} D^2 \dot{u} + C_d \frac{1}{2} \rho D u|u| \qquad 3.6)$$

Here C_m and C_d is the drag and inertia coefficient. ρ is the density of water, D is the diameter of a cylindrical element and u is the velocity of water.

However some structures are fitted with antifouling claddings that have performed reliably for more than 20 years [21]. Scouring on the other hand, is a form of erosion on the seabed that potentially can make the foundation unstable. However, this is not the case for jacket structures with conventional pile foundation because of the stability driven by axial loading on the legs and the degree of redundancy [38]. With that being said, scouring can potentially decrease the performance of jacket structures with bucket foundation. This is because of the suction mechanism between the foundation and the seabed

Figure 3-9 illustrates different damages occurring on offshore jacket structures [39-42]. Figure 3-9 (A) illustrates a through crack on a tubular joint caused by fatigue. Figure 3-9 Figure 3-9 (B) illustrates corrosion damage on a jacket structure in the air gap. This is as stated earlier a critical location for corrosion damage. Figure 3-9 (C) is typical buckling of a tubular member due to overload. The cause of this particular overloading scenario is unknown. Figure 3-9 (D) is a representation of marine fouling on the jacket legs, and is not directly defined as a structural damage but is a damage parameter resulting in an increase of drag force around the tubular member.

(A) Fatigue through crack

(B) Corrosion

(C) Buckling

(D) Marine fouling

FIGURE 3-9: A, B, C, D: DAMAGES ON JACKET

3.4 DISCUSSION

In the previous sections the failure modes of a jacket structure are listed and damage parameters are explained. Due to the use of sacrificial anode, the effect of corrosion damage on an offshore jacket is relatively easy to control. This is also stated in DNVGL-RP-C210 [43]. In comparison, the fatigue cracks can be more critical mechanisms due to uncertainties in crack propagation calculations and that sudden events, such as storms can result in rupture. Also dents and scratches need special consideration in addition to piles since they are unavailable during operation.

According to NORSOK N-005 [33], the objectives of condition monitoring for loadbearing structures are to ensure that an adequate level of structural integrity is maintained at all times. To accomplish this, the standard states: *condition monitoring shall determine, within a reasonable level of confidence, the existence, extent and consequence of:*

- *degradation or deterioration due to fatigue or other time dependent structural damage*
- *corrosion damage*
- *fabrication or installation*
- *damage or component weakening due to strength overloading*
- *damage due to man-made hazards*
- *excessive deformations*

As stated in Section 2.1 condition monitoring is defined as SHM and manual periodic inspections. Therefore the challenge in the context of this thesis is to develop an online SHM system that can satisfy these standardized criteria for loadbearing structures. The hypothesis of fatigue as a cause of the crack propagation is strengthened by the fact that the structures on NCS are exposed to an environment with consistent load cycles.

4. LITERATURE SURVEY – SHM OF JACKET PLATFORMS

This chapter summarizes knowledge obtained from earlier measurements done on offshore jackets and presents the different sensor technologies and their matureness. Initially, a table containing standards and recommended practices for monitoring is presented. This is followed by a general description of how monitoring is done today. A table containing descriptions and conclusions from earlier SHM projects on offshore jacket platforms is thereafter presented. Presented next is an assessment of the different sensor technologies available in literature. An historical overview of influential contributions to the advancements in vibration based damage detection is presented. Data processing methods and data evaluation algorithms are evaluated. Finally distributors of SHM systems that can be deployed on offshore jacket structures are described.

Table 4-1lists the recommended practices, ISO, and NORSOK standards containing information about monitoring procedures and techniques.

TABLE 4-1: MONITORING STANDARDS AND RP

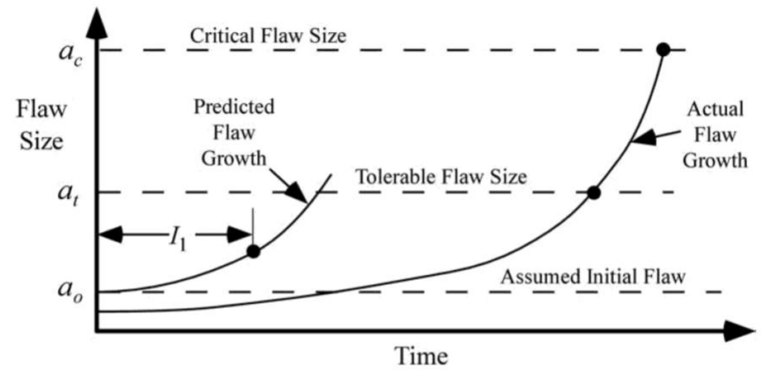
Standard	Title	Content
NORSOK N-005 [33]	Condition Monitoring of Loadbearing Structures	Annex A "Inspection methods" covers the most used inspection methods today, and also emphasizes on the possibilities of what they call Instrumentation Based Condition Monitoring (IBCM). IBCM can be used as an alternative to the conventional inspection methods. Annex C "Jacket structures" is a normative section of the code, containing additional requirements which is specific to the monitoring of offshore jacket structures.
NORSOK N-006 [44]	Assessment of Structural Integrity for Existing Offshore Loadbearing Structures	Summary of monitoring programs.
DNVGL-RP-C210 [43]	Probabilistic Methods for Planning of Inspection for Fatigue Cracks in Offshore Structures	Recommended practice for the use of probabilistic methods for inspection planning of fatigue damage.
ISO 13379 [5]	Condition monitoring and diagnostics of machines	Explanation of procedures that can be used to condition monitoring of machines.

4.1 Current Monitoring Situation

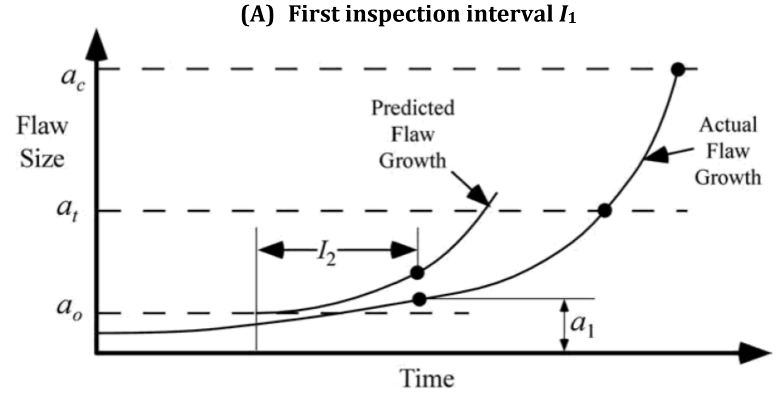
According to NORSOK N-005 [33], "*loadbearing structures used in petroleum activities shall throughout their lifetime comply with relevant national and international regulations. The loadbearing structures should be inspected, evaluated, assessed and maintained, in line with this standard and ISO 13819-1 "Offshore structures Part 1: General requirements"*". This means that according to standards, offshore jacket structures are obliged to have a monitoring program.

Today this is mainly done with periodic manual inspections by the use of varies NDT techniques applicable by ROV's but also divers are used. In Table A.1 in Annex A from NORSOK N-005 [33], the different NDT techniques and specifications are listed. These techniques are not explained any further in this thesis, because herein the focus is related to SHM systems and their applicability as an alternative to the NDT techniques that needs to be performed manually. According to NORSOK N-006 [44] risk based inspection (RBI) is a model often used to predict the inspection intervals. By taking into account failure probability and consequence, the risk of each failure mode can be evaluated and ranked. Hence, RBI is a tool for optimizing the inspection intervals making the manual inspection method more effectively. An example of one approach to predict the inspection intervals is to base it on the predicted flaw growth induced by fatigue damage. Figure 4-1 A, B, C illustrates the correlation between crack growth and inspection intervals [17]. Manual inspection is however expensive and includes risk of human life, therefore development of SHM systems are of major importance.

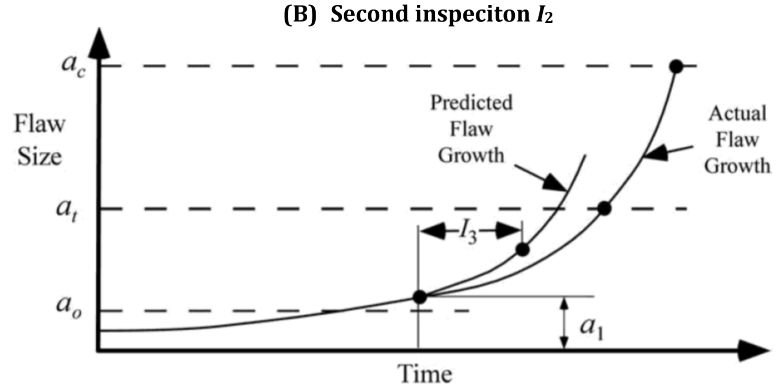
Following is an explanation of how the different damage parameters are evaluated today according to NORSOK N-005 [33]. As stated in Section 3.4 corrosion is not an extensive problem on jacket structures due to the use of cathodic protection. However the performance of the cathodic protection system is monitored by a ROV. Marine growth is of importance due to the direct relation to the Morrison equation as explained in Section 3.3.4. The monitoring is mainly performed by a ROV. The fatigue monitoring is done by various NDT techniques, mainly operated by a ROV. Fatigue assessment regarding the piles in the foundation of a jacket structure should according to NORSOK N-006 be based on the number of blows and the energy used during the installation of the piles. According to DNV GL RP-C210 [43], FM is used to establish crack growth curves and probabilistic analysis is used to include uncertainties in parameters used for fatigue damage. Figure 4-1 illustrates how the inspection period can be predicted due to the predicted flaw growth [17]. A structure is normally initially inspected before it is operational to establish the size of an initial flaw. The lower curve illustrates the actual crack growth, while the other curve describes the predicted crack growth. During the service life of the structure the crack growth is inspected to assess the condition of the crack. The flaw size needs to be within the largest flaw size that might be missed by a NDT technique (a_0) and the tolerable flaw size (a_t). The time it takes for the flaw to increase in size from a_0 to a_t is computed and the first inspection need to be within this time limit. If a new crack size a_1 is detected a new computation is needed to predict the time it takes for the flaw to increase from a_1 to a_t. Thereafter a new inspection interval is predicted within this new time limit.



(A) First inspection interval I_1



(B) Second inspeciton I_2



(C) Third inspection I_3

FIGURE 4-1 A, B, C: INSPECTION INTERVALS

4.2 Summary of Important SHM Projects

An extensive effort is done to obtain knowledge of earlier SHM projects. In the following table, an overview and short description of some of these earlier monitoring projects prepared for the Offshore Technology Conference (OTC) are presented.

Table 4-2: SHM Projects

<table>
<tr><th>Article heading</th><th>Keywords</th><th>Description</th></tr>
<tr><td>Measurement of Fatigue Performance of Forties Bravo [45]</td><td>Fatigue, Wave Devices, Forties Bravo, Particle Velocity Meter, Accelerometers, Strain Gauges</td><td>Fatigue assessment on a jacket structure by looking at the real time relationship between strain, displacement and wave time histories.
Conclusions that were drawn:
1. The strain response were dependent on location.
2. Most of the members had a short time strain amplitude distribution of a Gaussian nature, whilst the strain cycle distribution was of Rayleigh distribution.
3. The results could be explained by drag and inertia coefficients in Morison's equation.
4. Most of the fatigue damaged happened during wave heights over 6 m, hence storms affects fatigue damage tremendously.
5. In general, the measured characteristics matched the theoretical calculations.</td></tr>
<tr><td>Measured Dynamic Behavior of North Sea Jacket Platforms [46]</td><td>Jacket, SHM, Dynamics, Morison equation, Environmental monitoring</td><td>Describing the structural system behavior (dynamic response) of two platforms in the North Sea.
Conclusion that were drawn:
1. Strain was wave induced and quasi static.
2. Structure behaves linear before and after change of mass or stiffness.
3. The soil structure interaction had Coulomb type damping.
4. Nonlinear wave loading.</td></tr>
</table>

Article heading	Keywords	Description
Instrumentation of Ekofisk Platforms [47]	Environmental sensors, Jacket, Ekofisk, Strain sensors, Structural repsonse	Explanation of instrumentation set-up, sensors and measurement results on platforms located at the Ekofisk complex. Important conclusions that were drawn: 1. Ratio between predicted and measured deck displacements is similar to the predicted and measured axial stress. 2. The water particle velocity was overestimated compared when using Stokes 5th order wave theory.
Dynamic Behaviour of Kvitebjørn Jacket Structure – Numerical Predictions Versus Full-scale Measurements [48]	Jacket, Dynamic behavior, Kvitebjørn platform, Time domain, Morison equation	This paper compares measured response on the Kvitebjørn platform with predicted response. The overall conclusion was that measured response is less than the calculated response.
Full Scale Measurements at Magnus [49]	Jacket, Dynamic behavior, Magnus Platform, Accelerometers, Strain gauges	This paper describes a SHM system deployment on the Magnus Platform in the North Sea. Conclusions that were drawn: 1. Lower natural frequency than estimated during design. 2. Conservative drag and inertia coefficients in the Morison equation.
Monitoring Structural Integrity of North Sea Production Platforms by Acoustic Emission [50]	AET, Ninian Southern, Jacket, Cost consideration	Description of the use of acoustic emission testing on a jacket in the North Sea. Conclusions that could be drawn: 1. The value of AET monitoring was shown 2. Cost benefit
Online Structural Integrity Monitoring of Fixed Offshore Structures [51]	Vibration based monitoring, Jacket, Ninian Southern,	Description of the use of vibration based monitoring on a offshore jacket in the North Sea. Conclusion that could be drawn: 1. The applicability of vibration based testing and additional software was illustrated 2. The system set-up was effective to detect brace severance on a 4-legged jacket

Most of the earlier measurements done on offshore jacket structures was aimed to assess the accuracy of the structural models used in design and not directly related to monitoring of jacket structures for damage identification. . In this thesis the monitoring will be related to structural damage detection and not to obtain knowledge of environmental loadings for updated design procedures. Even so in the context of this thesis they contain valuable information about instrumentation set-up and monitoring procedures.

The two papers containing information about monitoring techniques used on the Ninian Southern Platform in the North Sea have been solid contributions to the understanding of monitoring systems specifically deployed for damage detection purpose. Both acoustic emission testing (AET) and vibration based damage detection methods are discussed. The two monitoring technologies are still being used and these reports have influenced the case study proposal in Chapter 6.

4.3 DATA COLLECTION

This section addresses the different technologies that are used in the offshore industry today, technologies from other industries and newly developed concepts. The target is to assess the suitability for developed technologies used in other industries and new type of sensors to detect the failure modes of offshore jackets. The techniques are divided in three different categories defined in Table 4-3, in the order of maturity of use in the offshore industry. Table 4-5 lists the structural monitoring techniques that are elaborated on further in this thesis. The techniques are listed together with their detection capabilities with the purpose of making an initial overview of the measuring techniques. Atkins Limited and Mecon Ltd. made a report for the British Health and Safety Executive (HSE) in 2009 [35]. The report was made during a comprehensive research about monitoring technologies and contained information about sensors used overall in the offshore industry, including offshore jackets. The sensor collection in this section is influenced by that report.

Table 4-4 lists the environmental monitoring techniques. These techniques are important for comparing structural response directly with environmental forces. However, these types of monitoring techniques are disregarded because they are not directly related to monitoring of structural integrity.

TABLE 4-3: DEFINITION OF MATURITY

Maturity	Description
Proven technology	Used in SHM of jackets today
Unproven technology	Used in SHM on other structures
State of the art	Technology not in broad use in any industry

TABLE 4-4: OVERVIEW OF ENVIRONMENTAL MONITORING TECHNIQUES

Response	Maturity	Techniques	Detection capability
Environmental	Proven	Wave buoy	Wave height Wave direction
		Wave radar	Wave height Wave period
		Current meters	Water particle velocity
		Anemometers	Wind speed

TABLE 4-5: OVERVIEW OF STRUCTURAL MONITORING TECHNIQUES

Response	Maturity	Techniques	Detection capability
Structural	Proven	Acoustic emission testing (AET)	Cracks Corrosion[1)] Strain
		Strain measurement	Strain
		Accelerometer[2)]	Member severance
		Flooded member detection (FMD)	Member leak Through cracks
	Unproven	Electrical resistance based corrosion Sensors	Corrosion
		Ultrasonic testing (UT) and Guided wave testing (GWT)	Cracks Corrosion
		Fatigue gauge	Cracks
	State of the art	Acoustic fingerprinting	Cracks Corrosion Strain
		Smart sensors	Cracks Strain

1) Difficult in a noisy offshore environment
2) When used with a vibration based damage detection method

4.3.1 PROVEN TECHNOLOGY

Acoustic Emission Testing (AET)

AET is in general a mature technology that mainly detects active fatigue cracks and fatigue initiation, but it can in some cases be used in corrosion detection as well [52]. The technology works in the way that sensors are placed around an element, where they are detecting acoustic emission caused by deformation/crack growth. The signal amplitude from crack growth makes the crack propagation relatively easy to measure with a distance of up to 5 meters between sensors [53]. The acoustic emission frequencies from such damages are usually in between 150 – 300 kHz, but the sensors normally samples up to 1 MHz [54, 55]. VALLEN Systeme is a company delivering AET equipment, including watertight AET sensors. According to their sensor catalogue, the suitable sensor frequencies are dependent on where the sensors are used. Difference in the propagation of signals in different materials and the mechanism of the signal source is the main reasons for the different frequencies needed. Table 4-6 is an overview of the different frequencies vs. application [56] .

Figure 4-2 illustrates an AET system detecting crack propagation [52]. The sensors are placed around the element surrounding the weld in such a way that the acoustic emission can be detected, and is commonly connected through an amplifier before the data is fed into an acquisition system processing the result. The last component in a typical AET system is a workstation displaying the test result.

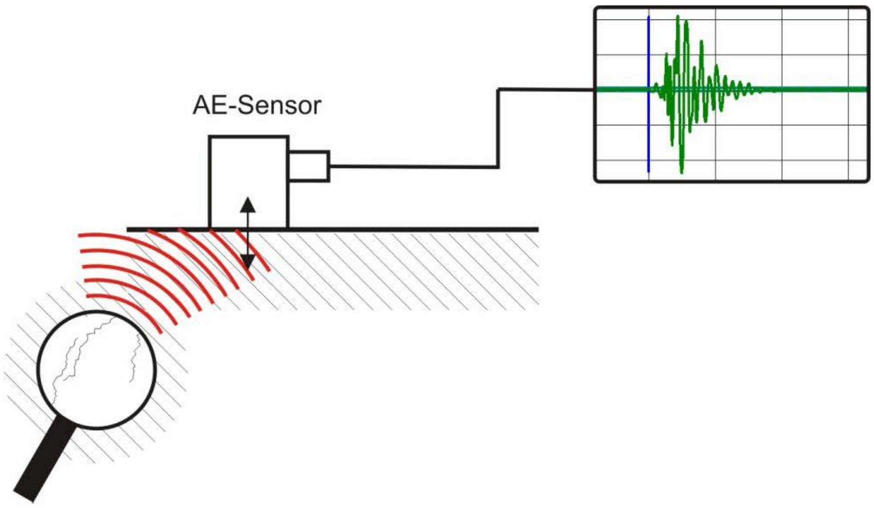


Figure 4-2: AET system setup

Table 4-6: Frequency ranges vs. application

Application	20-100 kHz	100-400 kHz	>400 kHz
Corrosion screening of flat bottom storage tanks	✓		
Leakage detection in water/oil pipelines	✓		
Hot reheat pipe crack detection		✓	
Integrity testing of pressure vessel		✓	
Partial discharge detection	✓ *	✓	
Integrity testing of metallic structures		✓	
Integrity testing of composite materials		✓	
Integrity testing of concrete structures	✓		
Drying process monitoring of plants/wood		✓	
AE-testing of small specimen			✓

*When noise is low

A paper from 1992 concerning the use of AET sensors on offshore jacket structures were discussed in Section 4.2 [50]. The conclusion from that paper was that the technology was suitable for detecting cracks on jacket structures. In 2014 Duthie and Gabriels made a thorough report on the matureness of AET systems on offshore platforms and a proposal for installation procedures in conjunction with the European Conference on Non-Destructive Testing in 2014 [53]. In the report they investigated the applicability of a SHM system for offshore structures delivered by VALLEN Systeme by using their product line of AE sensors, AE preamplifiers and AE signal processor in addition to VALLEN's own software. This multichannel AE system is called AMSY-6 and according to their catalogue [52] the system satisfy the standardized requirements for equipment and verification of operating characteristics of AET.

To get an understanding of the position and number of sensors required, the report recommended doing a feasibility study of the platform. The feasibility study needed to include a noise check and an acoustic survey performed by an acoustic emission specialist during a visit on the soon to be equipped platform. This is very important for AET systems, because the data retrieved from these types of sensors can be difficult to read when a considerable amount of noise is present. Further on, schematic documents of the platform and photographs from the visit were the basis for the system set up. This included among other things positioning of the sensors and routing of the cables. Before the equipment was shipped, it had to undergo a factory acceptance test where the principle functions were tested. After installation on the platform, the AET system needed to pass a site acceptance test before monitoring could commence. This test included the following checks: System response from a repeatable electronic source, sensor response with the system, remote control of the workstation, data transfer, and software function checks including alarms.

The workstation was featured with an automatic alarm and warning system that was initiated at predefined values defined by the acceptance criteria. The warning function activated on a lower value than the alarm. If the monitoring resulted in a warning, manual strain measurements was proposed to monitor the stress at the crack tip. This was due to that crack propagation is dependent on the stress at the crack tip. The maintenance of the AET system was relatively simple and included only logging on to a computer even onshore. The paper also stated that there was a sensor self-testing function within the VALLEN software. This worked in the way that each sensor sent out a pulse that was received from the remaining sensors.

In the offshore industry today, the AET system is mainly used in high criticality applications due to the high cost [35]. In history, the cost is mainly due to excessive wiring and that the interpretation of the signals was needed to be done by an engineer. The reason for highly qualified signal interpretation is because of complex signal data including a lot of noise from the sensor due to the harsh environment offshore. The results from the report from Duthie and Gabriels are indicating that these cost-issues are no more an obstacle, due to improvements in software, hardware and communication. Also wiring in the splash zone is not preferable due to wave forces, but an AET system can potentially be connected to a WSN system. Examples of a using wireless AET systems for structural monitoring of bridges has been found [57]. This is probably the solution for the future.

Strain Measurements

This is a technology used to evaluate local loading regimes [35]. This can result in vertical bending, horizontal bending, torsion, vertical shear force, and longitudinal compression forces [2]. Strain can be defined as the deformation of a material caused by the action of stress [17]. The strain is expressed in (4.1) where ΔL is the deformation in length and L is the initial length:

$$\epsilon = \frac{\Delta L}{L} \tag{4.1}$$

There are in general two forms of strain monitoring; dynamic and static. Static tests are often needed to be done in a laboratory with a test specimen. The operator can apply a specific load, collect the data and then increase or decrease the load for a new reading. The dynamic strain measurement on the other hand results in a continuous time-strain diagram and is performed at the actual structure. The goal of strain monitoring on a platform is to evaluate a time-strain diagram, therefore the dynamic measurement technique is needed. It is important to notice that dynamic strain monitoring requires higher sampling frequencies than the static test. This form of monitoring is possibly the most common SHM technique, and is used in many industries today, including offshore structures. The stress-strain relationship resulting from the dynamic measurement can be used to assess materials during operation. The strain sensor types mainly used today are electrical strain gauge, piezoelectric strain sensor and optic fibre system [58].

Electrical strain gauge can be divided in two, namely metal foil gauges and vibrating wire. The former technology measures the change in electrical resistance when a metal foil is undergoing strain [58]. The foil gauges are common in strain measurement of offshore platforms [59]. The sensor will detect an increase of the electrical resistance when the foil increases its length. (4.2) express the relationship, where r is the specific resistance, L is the element length and A is the cross sectional area:

$$R = r\frac{L}{A} \tag{4.2}$$

On the other hand, the vibrating wire sensor measures change in frequency of a vibrating wire when load in the form of tension is applied. Vibrating wire technology is well known for having a long-time stability. There has also been a significant amount of vibrating wire sensors used on offshore structures [60]. (4.3) express the fundamental relation behind the sensor technology [61]. Where F is the frequency of the string and L is the string length whilst T and μ is notations of the string tension and the mass of the string.

$$F = \frac{1}{2L}\sqrt{\frac{T}{\mu}} \tag{4.3}$$

Piezoelectric strain sensors use the properties of piezoelectric materials as lead zirconate titanate (PZT). The piezoelectric material is a material that produces electricity when crystals get deformed. According to the Oxford dictionaries, the definition is: "Electric polarization in a substance (especially certain crystals) resulting from the application of mechanical stress" [62].

Optical fibre is the technology of light transmission through glass or plastic [63]. One form of this technology is called fiber bragg grating (FBG). This is a promising technology which has been given more attention during the past years. The FBG is exposed to a light source and the gratings will reflect certain wavelengths based on the properties of the gratings. Parameters like strain or temperature will move the gratings and change the gap between them. Change of the gap between the gratings also leads to a change in reflected wavelength and this can be converted to a value of strain [58]. A paper investigating the potential of FBG sensors on offshore jacket structures was found [64]. The following definitions could be established from this paper. (4.4) defines the bragg wavelength λ_B. Here $n_{eff}$is the effective refractive index of the fiber core and Λ is the grating period. Strain affects the grating period and temperature affects the refractive index [64].

$$\lambda_B = 2n_{eff}\Lambda \tag{4.4}$$

The FBG sensor with the protection layers containing steel and epoxy is illustrated in

Figure 4-3 together with an illustration of the reflected wavelength [64]. The paper used a model of a real four legged jacket platform located in the yellow sea and performed calibration with static loading followed by a measurement period with dynamic loading. The conclusions that could be drawn were that the FBG technology was applicable to be used as acceleration and strain sensors. They proved this by comparing the strain measurements done by the FBG sensors with a strain gauge, and saw that the FBG sensor gave the same results. It was a paper from the University of Nankai stating the disadvantages with the FBG system and elaborated on how the FBG system could be implemented in a WSN to overcome these. Disadvantages come with the need of a light source, which leads to a limit in the extent and the flexibility of the fibre cable [65].

It is observed through literature that the FBG sensors are not widely used on offshore structures, but mostly on civil structures. However, there was found a paper describing a real set-up of wireless FBG sensors on a jacket structure in China [66]. In this thesis, the potential of the FBG system will be in focus also for other measuring techniques e.g. accelerometers. The other strain gauges mentioned are more sensitive to the environment compared to the FBG sensors. Therefore one challenge with those sensors is to protect the gauges from the harsh environment offshore. However, research show that there exist protection techniques of ordinary electrical strain gauges [59] and examples of successful use of protected sensors in a SHM system [47]. With that being said, the FBG sensor is superior due to excellent resolution and range, immune to electro-magnetic interference, water and corrosion resistance, ability to have distributed sensors, immunity to harsh weather condition and reasonably low cost [67].

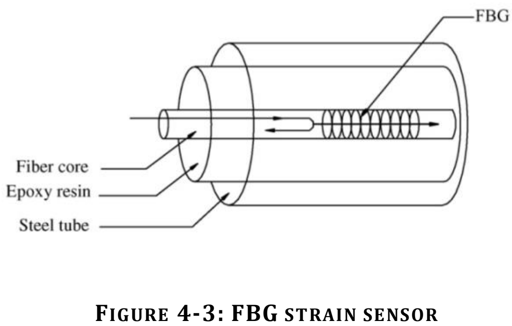


FIGURE 4-3: FBG STRAIN SENSOR

Accelerometers

These are commonly made of piezoelectric material and register applied accelerative forces when a structure is moving. There is also use of FBG accelerometers as a fibre optic alternative to the piezoelectric sensor [64]. The FBG accelerometer has all the same advantages compared to the piezoelectric sensor, as elaborated on in the strain sensor section. Accelerometers do not provide any direct knowledge about damage but can be a tool to find the dynamic characteristics. Further the dynamic characteristics can be parameters identifying damage. This is discussed further in Section 4.4. Accelerometers are the main sensor used for vibration based damage detection and therefore there are many examples of its applications on offshore jacket structures from the 70's until now.

Flooded Member Detection (FMD)

This is a measurement method dependent on primarily radiographic or ultrasonic technology. Radiographic technology is the transmission of light (e.g. x-rays or gamma rays) through a member. Some of the light is absorbed by the member due to density and material composition, and the passing light will be detected by a detector, making up a picture of the member inspected [68]. Ultrasonic technology is described in the section of UT and GWT sensors. According to the flooded member detection catalogue of Fugro [69], the advantage of the radiographic technology is that it is quicker and more reliable than the UT technology.

Fugro delivers a FMD system called "SureFlood", developed by Fugro and The University of Western Australia. This system relays on radiographic gamma rays, since they as previously mentioned have concluded that radiographic technology is better than UT [69]. There is limited information about the use of the SureFlood system.

4.3.2 Unproven Technology

Electrical Resistance Based Corrosion Sensors

This technology works in the way that an ER probe is equipped with an element freely exposed to the corrosive environment and a reference element inside the probe [70]. The main purpose is to discover corrosion and the technology is applicable both with the use of a probe or by connecting a sensor to a WSN making it an online system. The principle of this method is to detect a decrease in electrical resistance of the material inspected. The formula for electrical resistance from the definition behind the strain foil gauge is used again here. As stated in Section3.3.2, corrosion results in metal loss which results in an increase of the electrical resistance according to (4.2), no offshore application is found in literature. Figure 4-4 illustrates the schematic description of the sensor [70].

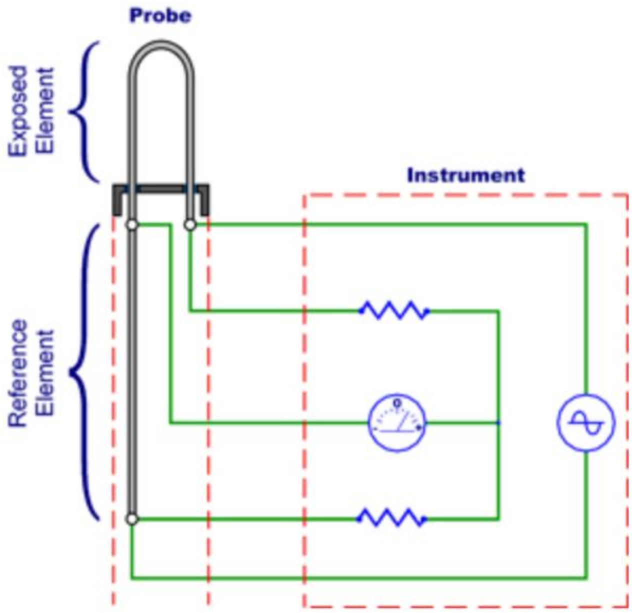


FIGURE 4-4: SCHEMATIC DESCRIPTION OF AN ER PROBE

Ultrasonic testing (UT) and Guided Wave Testing (GWT)

UT is a technology similar to AET. Whilst AET systems listen to ultrasonic waves, the UT both induces and receives the ultrasonic waves. By detecting the time interval between sending out the signal till it receives the signal as an echo, it is possible to both detect damage (degree of noise in the received frequency) and also calculate the location of the damage by calculating distance. The calculation of distance is defined in (4.5):

$$distance = \frac{elapsed\ time \cdot speed\ of\ sound}{2} \tag{4.5}$$

There are a significant number of different ultrasonic testing types. These types are respectively called A, B, C, D and P scan. The A scan is a scan in one dimension, whilst the B, C and D scans are two dimensional scans in different orientations. The B-scan is in cross sectional view, C-scan is in plan view and D scan is in end view. The P scan combines B and C scans into a three dimensional picture [71]. The different scans are illustrated in Figure 4-5 [71]. The advantage of using a P scan is that fake data captured by one scan can be evaluated again by the second scan from another angle, removing any wrong results. This makes the system more redundant and a remarkable tool for failure identification.

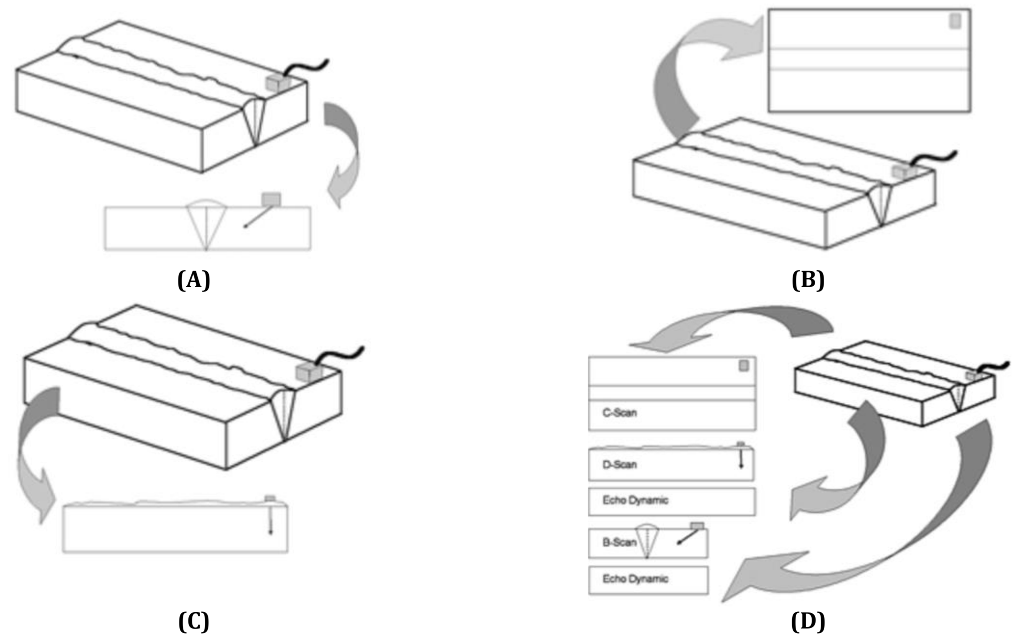


FIGURE 4-5 A, B, C, D: B, C, D AND P-SCAN

The GWT system works in the same principle as the widely used UT method, in fact the GWT system is sometimes called Long Range Ultrasonic Testing (LRUT). The difference is that the GWT system does not include any probes. The GWT system is normally a belt strapped around the element of inspection, as can be seen in Figure 4-6 [72].

The design gives the system the ability to do an A-scan in both ways making the range of measurement increasingly high compared to an UT probe which only measure in the point where the probe is set. The range of the scan is dependent on the ultrasonic frequency, where low frequency results in longer range and high frequency results in shorter range. The decision criterion is based on that low frequency results in lower sensitivity of the measurement.

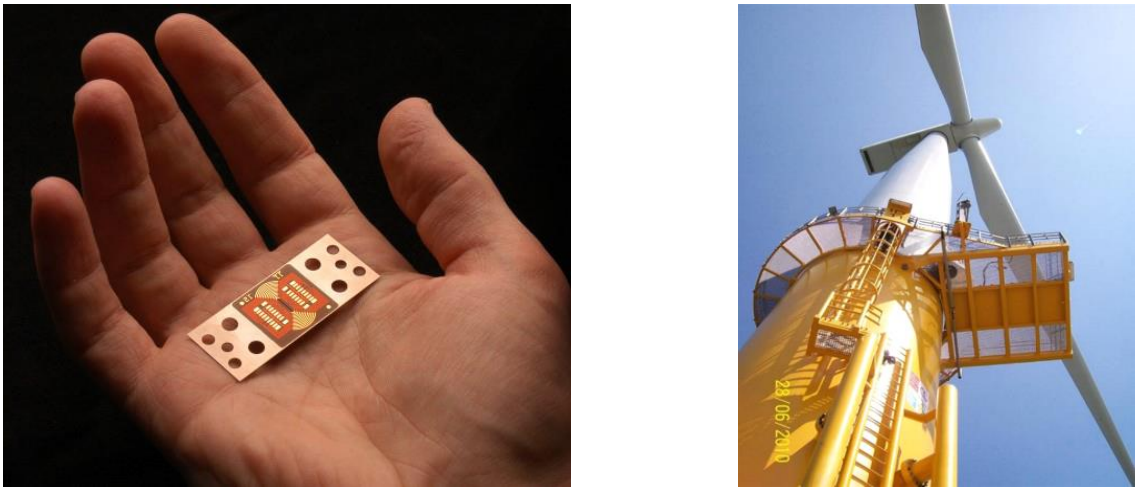
The GWT system is mainly used in pipeline inspection, detecting critical corrosion areas under isolation on the pipe and offshore applicability has been documented [72]. However, there are no papers on the applicability of GWT on jackets structures and little research on crack detection. In normal conditions it is possible to screen 25 meters each direction from a transducer. In other words, the total screening length becomes 50 meters, making this a highly effective measuring technique. However, the range of detection is highly dependent on the quality of the material being screened. As an example, corrosion will reduce the range because the energy of the screening will be scattered by the rough surface [72]. GWT using longitudinal waves cannot detect any longitudinal cracks. However, a torsional wave can in theory detect cracks because of the shear stresses that will be reflected. The similarity with regards to geometry between a pipeline and a hollow tubular member are major. Hence, the possibility of using GWT systems on the tubular elements on the jacket structure for corrosion or cracks is confirmed. This would be a highly effective damage detection system especially for monitoring welded connections.

FIGURE 4-6: GWT BELT

Fatigue Gauge

CrackFirst™ is a fatigue sensor patented in 1990. This is a sensor developed by the companies TWI Ltd, FMB, Micro Circuit Engineering Ltd, UMIST and Caterpillar. These days the sensor is licensed by the company called Strainstall, and they are the only ones who can deliver the system to the end user. According to Strainstall's catalogue the CrackFirst™ sensor works in the way that it can evaluate the accumulated lifetime of the element it is attached to [73]. This is done by analysing the crack growth due to fatigue of a pre-crack on the material shim placed near a joint of interest. There are twelve electrical tracks on each side of the pre-crack. Hence, the electrical output of the sensor will be changed while the crack propagates and breaks the tracks. Figure 4-7 (A) is an illustration of the sensor, showing the pre-crack in the middle [73]. The sensor can be protected from mechanical damage and corrosion by fitting a sealed enclosure over the installation area. In the catalogue, it is stated that remote operation is possible by using a WSN.

The applicability of the sensors on offshore structures is described in a paper by Faulkner, Cutter and Owens. The paper discusses the use of CrackFirst™ sensors on offshore wind turbines in the UK [74]. The aim of the monitoring was to uncover the effect of a design flaw on offshore wind turbines with a monopile type substructure. The sensors were placed primarily at a grouted connection between the monopile and the transition piece since it was the design of the grouted connection that had a reported design failure. Figure 4-7 (B) illustrates a monopile wind turbine structure [74]. Concluding remarks about this sensor will be that since they are proved helpful on offshore wind turbines, these sensors definitely have potential to be applicable on offshore jackets.



(A) (B)

FIGURE 4-7 A AND B: CRACKFIRST™ SENSOR AND A MONOPILE STRUCTURE

4.3.3 STATE OF THE ART

Acoustic Fingerprinting

The HSE report "Structural integrity monitoring - Review and appraisal of current technologies for offshore applications" described a technology that was new in 2009 based on the acoustic method called acoustic fingerprinting [35]. The basic idea was to transmit acoustic waves into the jacket legs and listen for any abnormalities in the reflection time of the signals. This made it similar to an AET system, only the acoustic fingerprinting would be an active technology and not passive as the AET technology.

The strength of the acoustic fingerprinting technology was that both transducers and receivers could be installed on top of the legs above the water level. For long range detection, the sensors were designed to couple to longitudinal compression waves. By placing all the equipment above sea level, it would lead to reduced cost during installation and operation. This is also something the industry demanded according to the feedback the industry had given to HSE. HSE made several reports during the development of the acoustic fingerprinting technology [75, 76]. These reports are the background for the discussion below.

The aim of the project initiated by the HSE was to develop a damage detection method using long-range propagation of acoustic signals on offshore jackets. The detected damage was cracking or flooding of hollow members of the jacket. The project was divided into two parts. In the first part of the project, the method was tested on a 2D model made out of polycarbonate material. Preferably there should have been used a steel model but due to restricted resources the "plastic like" polycarbonate material was used. The polycarbonate material was chosen due to that the speed of sound in this material is 1:25 of the speed of sound in steel. This is a modest scaling factor compared to use of other materials, making the effect of the acoustic waves as realistic as possible compared to a real jacket structure. Also, the material was chosen due to the fact that damping of the compression waves we want to measure in polycarbonate is higher than in steel. This made the model able to have higher damping properties in air, then of a rig of steel would have in water.

The model used was in the dimension 1/100 of the Claymore jacket, located in the North Sea. There was also developed a numerical model so that it was possible to compare numerical and experimental results. The second part of the project was similar to part one, but used a 3D model of the upper half of the Claymore jacket. By testing the method on a more advanced geometry, the limitations of the method could be explored. The tests were done with two methods. Method No.1 was called tomographic geometry, which basically was that the transmitters were placed on the top and the receivers placed on the bottom. By using this method the signals are actually traveling through the damaged section. Method No.2 was called reflection geometry, placing both the transmitters and receivers on the top of the jacket legs.

Results from both the numerical and experimental model were promising. Satisfying measurement was made when an element of the jacket was exposed to a cut made by sawing of a member. However, the reports actually concluded that the acoustic fingerprinting system was more or less a FMD system because it was basically the flooding of the members that was detected, and not the through cracks. They tested two different damage detection algorithms, and the successful damage localization algorithm was something they called least mean square (LMS) imaging method. This method was built on the principle of process only the earliest-arriving damage event. According to their result, the tomographic geometry method had limitations regarding localization vertically. This was explained by the fact that the vertical position of an occurred damage had a small impact on the time of arrival of the first damage event for transducers close to the vertical leg that had the damage. The reflection method did not suffer from this drawback because the time of arrival of damage events was very sensitive to the vertical position of the damage.

Even though the reflecting geometry method showed more potential than the tomographic method, it also had some limitations. First and foremost signal stability is of major importance when using this type of technology. The reports mentions signal drift as the biggest obstacle during testing on the model. It was stated that most of the sources of frequency drift in the testing would not occur on a real jacket platform. However, other sources of frequency drift can occur offshore on a real jacket structure. The effect of tidal change on the water level and also wave forces on the jacket structure was mentioned as the biggest contributors to signal drifting offshore. It should definitely be possible to identify and remove the noise from both tidal effects and wave loads due to their cyclic and periodic characteristics. Also, frequency drift caused by change of mass distribution on the topside can occur. On the other hand, the HSE report contained a proposal for how to also avoid this last source of error. According to available information there are no examples of further tests done since 2009.

Smart Sensors

Smart sensor is defined as a sensor that includes these 5 features:

1. On-board microprocessor
2. Sensing Capability
3. Wireless communication
4. Battery powered
5. Low cost

Thorough investigations of the use of smart sensors in SHM have previously been done [77, 78]. Similarly to the WSN development, smart sensor technology has emerged in the past years, due to improvements in sensing, communication and data systems. It is especially the capability of local data processing using micro electro mechanical systems (MEMS) and automatic communication between the sensors that makes this technology unique and an important addition to the wireless sensor technology. This makes the sensors capable of processing data locally, and therefore transmits only important information to the manned workstation. This makes the final damage evaluation go quicker because only the data contributing to change in the damage evaluation is processed. In contrast, the centralized data processing model needs to process all the collected data from the sensors. As an example, it is stated in a report on the use of smart sensors from the University of Illinois [77] that two bridges in Hong Kong called Tsing Ma and Kap Shui Mun produce individually 63 MB of data every hour due to the high sampling frequency. Use of smart sensors will decrease the CPU effort by filter out unnecessary data locally with "if-then" decisions. Figure 4-8 illustrates the difference of centralized and local data processing [77]. The dashed lines represent the remaining of the filtered data.

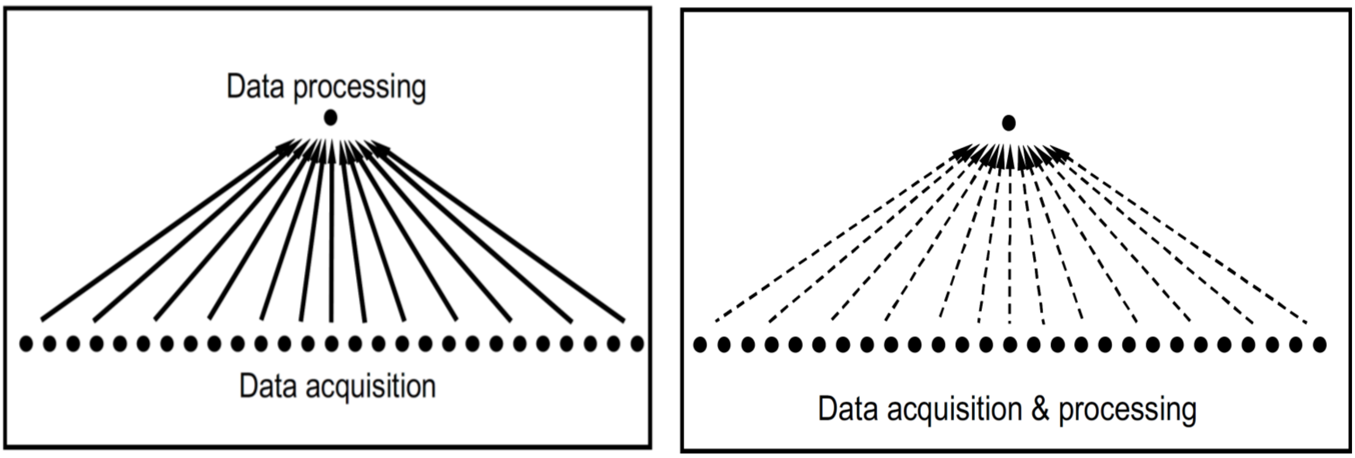


Figure 4-8: Centralized vs. independent data processing

Figure 4-9 illustrates the main components of MEMS; microelectronics, micro sensor, micro actuator and micro structural elements [77]. Furthermore, by using only wireless sensors wiring will be unnecessary which may bring the total installation cost potentially down to an acceptable level. However, the information available from the studies of smart sensors points out some limitations which are worth mentioning. The CPU power of the MEMS is limited compared to a normal computer, which slows down the system and makes it potentially not work as a real time monitoring system, resulting in a longer response time between when a damage occur to the operator can respond to the damage. Also, battery power is mentioned as a limitation that needs to be dealt with in the future. Battery power limits the system to do computational tasks over a certain limit.

According to the paper on smart sensors [78], three different sensors implemented as smart sensors has a potential for civil structures; Fibre optic sensors, Piezoelectric sensors and Magnetostrictive sensors (a form of GWT sensor). All of these sensors are similar to the once mentioned in the above sections, but have the five smart sensor features implemented. Smart dust is a term often used in association with smart sensors. The term is describing hundreds or thousands of MEMS connected together in a network. The ultimate goal is to make the MEMS in the magnitude of just a cubic millimetre and distribute these onto a structure of interest. However there is a long way before the technology of making MEMS of that magnitude is available.

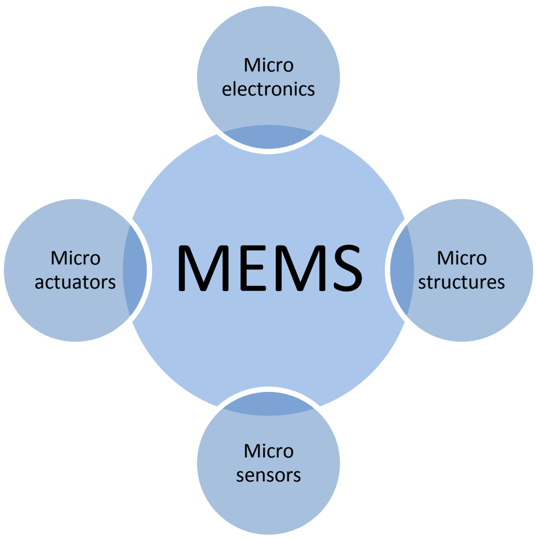


FIGURE 4-9: COMPONENTS OF MEMS

4.3.4 Sensor Summary

Table 4-7 summarizes relevant information gathered about the sensors assessed in this thesis. The table is produced in the intent to be a help for getting an overview of the most applicable sensors for offshore monitoring and their most important parameters. There are 5 parameters in total.

The first two are regarding structural and electromagnetic noise immunity. Structural noise is a term for vibration or sound generated by for example wave loads onto the jacket structure, vibrations from process equipment and disturbance by the rotors of a helicopter in service close to the platform. Electromagnetic interference is defined as electromagnetic noise from lightning, solar flares or disturbance from the northern light. The sensors are given the label low, medium or high according to their immunity against these two types of noise that can have an impact on the sensors and the gathered measuring data.

Mounting are configurative characteristics that are important to have knowledge about when evaluating sensors. The possibility of mounting the sensor on the exterior of the structure (surface mount) or if it can be embedded into the structure is of importance. This former option is preferable if the aim is to monitor an existing structure, whilst the latter mounting technique gives the sensor exceptional protection and is most practical to use while monitoring a structure which is not yet build.

WSN compatibility is an important function for future measuring. The direction of the advancement in SHM is clearly to use large WSN systems on structures. Development within MEMS and smart dust are contributing factors to this view of the future monitoring systems. The maturity of all the different sensor types is graded either low, medium or high.

TABLE 4-7: SENSOR OVERVIEW

Technology	Sensor	Structural noise immunity	Electrical interference immunity	Mounting	WSN compatibility	Maturity on offshore jacket platforms
Electrical	Foil strain gauge	Low	Low	Surface-mount	N/A*	High
	Vibrating wire gauge	Low	Medium	Embeddable	N/A*	Low
	ER corrosion sensor	High	Low	Surface-mount	✓	Low
	Fatigue gauge (CrackFirst™)	Low	Low	Surface mount	✓	Low
Piezoelectric	PZT strain sensor	Low	Low	Surface-mount	✓	High
	AET	Low	High	Surface-mount	✓	Medium
	PZT acceleration sensor	Low	Low	Surface-mount	✓	High
	Acoustic fingerprinting	Low	High	Surface-mount	✓	Low
Optical	FBG strain sensor	High	High	Surface-mount and embeddable	✓	Medium
	FBG acceleration sensor	High	High	Surface-mount and embeddable	✓	Medium
Ultrasonic	GWT	High	Low	Surface mount	✓	Low
Radiographic	FMD	High	High	Surface mount (but can be embedded)	N/A*	High

4.4 VIBRATION BASED DAMAGE DETECTION ON OFFSHORE JACKETS

Vibration based damage detection is a vast research area. In this section, the research evaluated as most important advancements within vibration based damage detection with respect to offshore jackets are evaluated in a historical perspective.

The oil industry started with vibration based damage detection already in the 70's [10]. A conference proceeding by Vandiver made for the OTC in Texas in 1975 may be the first proof of any attempt to measure dynamic response of fixed platforms [79]. In the beginning, frequency change was used as damage indicator. From Chapter 3, the equation for the natural period of a jacket is defined in (3.1). By converting (3.1) to define the natural frequency instead of natural period, it yields:

$$F = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{4.6}$$

From (4.6) it can be seen that the frequency change is dependent on stiffness and mass, which both are parameters affected by damage. This made researchers believe that frequency change could be a suitable measure of damage of a structure. The damage identification was done by looking at the change of the natural frequencies of the jacket structure.

Figure 4-10 is a typical acceleration power spectrum for a jacket structure and this is the basis for identifying difference in modal frequencies induced by damage [80]. Mainly the changes in the three fundamental dynamical modes were assessed. According to the conference proceeding, the reason for evaluating these modes was because they easily are excited by the ambient loadings of wind and waves on an offshore jacket structure. The three fundamental dynamical modes consist of two swaying modes along the X- and Y-axis as well as a torsional mode around the Z-axis. These are illustrated as seen in the X-Y plane in Figure 4-11 .

A change in the frequency spectrum can be obtained by comparing updated measurements from accelerometers placed on the structure with measurements from the undamaged structure. However, research showed that there were two problems with frequency change as an indicator. First and foremost damage in the jacket structure needed to be highly severe to influence a frequency change. Secondly, factors like marine growth, equipment noise and change of the jackets center of gravity induced a frequency change, resulted in fake damage evaluation [10].

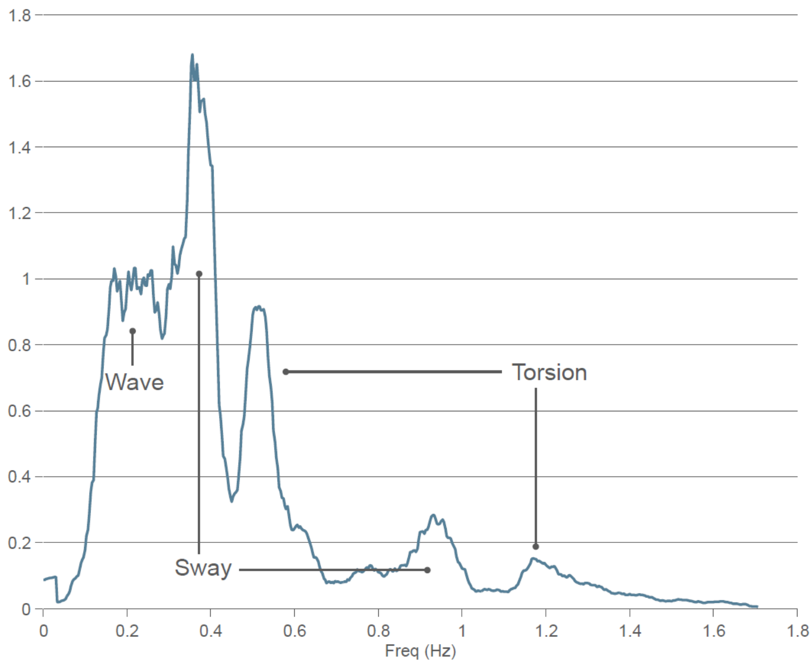


FIGURE 4-10: POWER SPECTRUM

To overcome these difficulties of using frequency as a damage indicator for global damage on offshore jackets, two papers proposed new methodologies including an alternative damage indicator respectively in 1983 and 1986. The first paper was made by Rubin and Coppolino for the OTC in Houston, whilst the paper from 1986 was made by Shahrivar and Bouwkamp from San Jose State University and University of California [81, 82]. The two papers discussed the use of modal shapes as a measure of damage instead of frequency on a k-braced jacket structure.

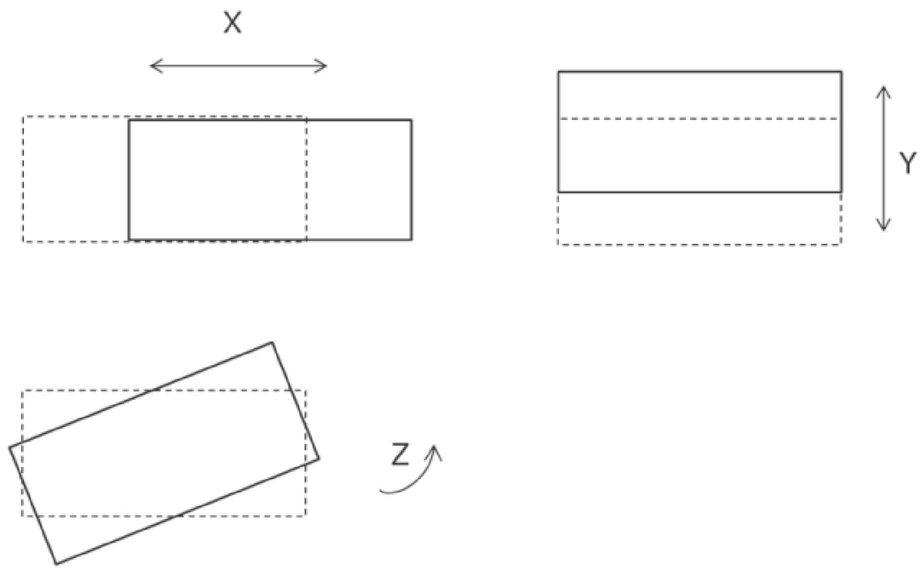


FIGURE 4-11: FUNDAMENTAL MODE SHAPES

The conclusions that could be drawn from these two papers were that mode shapes was more sensitive to damage than Eigen frequencies. Numerical examples of this statement was provided in the paper by Rubin and Coppolino [81]. They concluded that damage reduced the frequencies by 1-4% and changed the values of normalized modal deck displacements by 30-100%. Also the effects of marine growth, equipment noise and change of the jackets center of gravity could be differentiated from damage by measuring the mode shapes by looking at the normalized components of modal displacement.

The results showed that there was a big difference in these parameters when there was a change in mass and during damage. In addition, the paper by Shahrivar and Bouwkamp concluded that instrumentation below water surface was not required. It is important to notice that these two papers only assessed the forward problem of identifying damage, but not the backward problem of locate and estimate the degree of damage.

A paper written by Kim and Stubbs at the Texas A&M University in 1995 proposed a modal identification methodology for offshore jackets and also solved the backward problem [83]. In addition they solved further problems with jacket structures which were to locate damage:

- with many members
- for which only few mode shapes available (≤ 3)
- for which baseline modal responses was not available
- in a dynamic environment of modeling, measurement, and processing uncertainties.

The paper by Kim and Stubbs aimed to solve the three first damage location problems above. They presented an algorithm for damage localization and severity estimation also based on mode shapes. Only modal parameters from after the damage had occurred were available. The fundamentals as defined in [83] is presented in the following. (4.7) is the definition of the damage localization indicator β_{ij} for the jth member and the ith mode.

$$\beta_{ij} = \frac{E_j}{E_j^*} \tag{4.7}$$

The damage location indication is the ratio between the two parameters E_j and E_j^* representing material stiffness properties for the undamaged and damaged member. Further, the damage severity was based on a change in stiffness denoted α_j for the jth member:

$$E_j^* = E_j(1 + \alpha_j) \tag{4.8}$$

The theory was tested in a numerical example of an offshore jacket platform by using FE software. By looking at the result the proposed theory managed to locate and estimate the degree of damage, even though the algorithm tended to overestimate the damage. The overestimation was due to that the elemental stiffness that is one of the parameters in the material stiffness properties E_j^* and E_j was assumed to be similar for the damaged and undamaged element.

While the offshore industry cut back on research on vibration based damage detection, new damage indicators were tested in the civil engineering community and also in the aerospace industry. In 2002, Shi and Law from Hong Kong Polytechnic University and Zhang from Nanjing University of Aeronautics and Astronautics proposed a damage detection and localization method by using modal strain energy change (MSEC) as a damage indicator [84]. The proposed algorithm was used both on a numerical FE-model and experimentally with a two story steel frame.

Here the modal strain energy is defined as in [84]. Modal strain energy is the product of the elemental stiffness matrix and the second power of the mode shape component as formulized in (4.9):

$$MSE_{ij} = \Phi_i^T K_j \Phi_i \tag{4.9}$$

Where Φ_i is the mode shape component for the ith mode and K_j is the stiffness matrix for the jth element. The modal strain energy for the damage structure is defined as:

$$MSE_{ij}^{d} = \Phi_i^{T^d} K_j \Phi_i^d \tag{4.10}$$

The undamaged stiffness matrix is used in both equations since the stiffness matrix after damage is unknown. This is the same simplification as seen in earlier methods as explained in correlation with (4.7) and (4.8). From (4.9) and (4.10) the MSEC can be derived as the difference:

$$MSEC_{ij} = \Phi_i^{T^d} K_j \Phi_i^d - \Phi_i^T K_j \Phi_i \tag{4.11}$$

When the $MSEC_{ij}$ was established the modal strain energy change ratio (MSECR) for all the modes could be derived as:

$$MSECR_{ij} = \frac{\left|MSE_{ij}^d - MSE_{ij}\right|}{MSE_{ij}} \tag{4.12}$$

If more than one of the modes were available, a more certain answer could be obtained. According to the paper by Shi, Law and Zhang, the elements corresponding to nodal points of the mode shapes could give wrong indication of the damage localization. The normalized $MSECR_{ij}$ with respect to the largest $MSECR_{ij}$ was obtained to overcome this localization problem:

$$MSECR_j = \frac{1}{m}\sum_{i=1}^{m} \frac{\left|MSECR_{ij}^d - MSECR_{ij}\right|}{MSECR_{ij}} \tag{4.13}$$

The conclusions made were that MESCR could be a suitable tool for damage detection and localization due to its sensitivity to damage. With that being said measurement noise and incomplete measured modes affected the results. However, by using the result from more than one mode, successful results were obtained. As described later in this section, this paper influenced research on MESC for offshore platforms as well.

In 2005, Choi from Korea Institute of Nuclear Safety, Park from Youngsan University and Stubbs from Texas A&M University introduced a new form of damage indicator [85]. The method utilized the changes in the distribution of the compliance of the structure. There were earlier studies on using compliance change as a damage indicator, e.g. the contribution from Pandey and Biswas [86], but that study resulted in a method that were restricted to only damage localization by using the change in flexibility matrix. Hence, this paper proposed a method that should both localize and evaluate the damage severity. The change of compliance of the structure was obtained by using the mode shapes before and after damage. In (4.14) the compliance index β_{ij}^c for ith modal vectors and the jth element is formulized as in [85]:

$$\beta_{ij}^c = \frac{S_j^*}{S_j} \tag{4.14}$$

The compliance of element j when damaged had occurred was denoted S_j^* and S_j the compliance before damage. The methodology was tested on a simulated simple beam and a continuous beam. To compare the simulated results, the method was also tested on an experimental free beam structure. The study continuously compared results to earlier energy change methods. The substantial conclusion from this study was that the compliance index method could be used for damage localization and severity estimation. Other conclusions that were drawn were that the method was accurate and it yielded less error than existing methods based on energy change. There are no examples of this method being developed for offshore jacket structures. However the paper is mentioned in this section as an example of damage indicators used in civil engineering with potential for application on offshore jacket structures.

Focus on vibration based damage detection on offshore jacket structures was again initiated in 00's and now the offshore industry could learn from the developments in civil engineering and the aerospace industry. In 2006, Hu from University of Rhode Island, and Wang and Li from Ocean university of China presented Cross-modal Strain Energy (CMSE) as a new method of damage severity estimation [87]. A paper by Amiri and Asgarian from Toosi University of Technology together with Ghafooripour from Islamic Azad University was published in 2009 [88]. This was a paper on damage detection of offshore platforms by combining the MSEC procedure that was used in the paper by Shi, Law and Zhang [84] too also include CMSE.

MSEC was used to localize damage and CMSE was used for severity assessment of the localized damage. MSEC is defined in (4.11) and the damage localization procedure is the same as in the paper by Shi, Law and Zhang. From [88], the CMSE for the ith mode of the undamaged structure and jth mode of the damaged structure was defined as:

$$C_{ij} = (\phi_i)^T K \phi_j^d \tag{4.15}$$

The paper from Amiri, Asgarian and Ghafooripour was according to available literature the first attempt to use MSEC as a damage indicator for offshore jackets. The paper concluded that the MSECR accurately obtained the severity of damage and that CMSE was a good damage severity estimator. However, it was stated that the proposed method needed further calibration on real structures to be practical on an actual jacket structure.

In 2010, Hillis from the University of Bath and Courtney from the University of Bristol published a paper on SHM of jackets using the bicoherence function of ambient vibration measurements on offshore jackets [89]. This was a methodology that was specifically developed to find nonlinear fatigue damage. As stated in Section 2.2.2 the nonlinear behavior can occur due to opening and closing of fatigue cracks. The bispectrum is in other words a method for analysis of nonlinear signals. The paper concluded that the method could be a tool to show that small damages as low as a 10% stiffness reduction of a member could be detected. The method was not as affected by change in mass as the methods of frequency change or mode shape change would. The bicoherence theory is hereby defined as in [89]. A signal $y(t)$ has a FT:

$$Y(\omega) = \int_{t=-\infty}^{\infty} y(t)\exp[2\pi jwt]\, dt \tag{4.16}$$

And a power spectrum:

$$P(\omega)=\mathrm{E}[\mathrm{Y}(\omega)Y^{*}(\omega)] \tag{4.17}$$

Here * is representing a complex conjugate and E[...] denotes an expectation value operator. The bispectrum of the signal is then:

$$B(\omega_1, \omega_2) = E[Y(\omega_1 Y(\omega_2)Y^{*}(\omega_1 + \omega_2)] \tag{4.18}$$

By comparing (4.17) and (4.18), the nonlinear suitability of the bispectrum becomes clear. While the power spectrum includes only one frequency ω, the bispectrum is based on three frequencies: ω_1, ω_2 and $\omega_1 + \omega_2$. This makes the bispectrum a tool to evaluate nonlinear systems. To estimate the degree of coupling between signals the bicoherence was established as:

$$b(\omega_1, \omega_2) = \frac{|B(\omega_1, \omega_2)|}{\sqrt{E[|Y(\omega_1 Y(\omega_2)|^2]E[|Y(\omega_1 Y(\omega_2)|^2]}} \tag{4.19}$$

The bicoherence function was then used to make scatter diagrams of the acceleration response for the different damage scenarios. From the plots, damage could be detected and the damage index showed great applicability to discover damage on a fixed offshore platform subjected to ambient loading.

After 2010, the focus went from finding alternative damage indicators, to improve the data processing and evaluation models. In 2011, Mojtahedi from Osaka University and Lotfollahi, Abbasidoust and Ettefagh from the University of Tabriz developed a SHM method for offshore jackets using modal updating and modified artificial immune system (AIS) algorithm [90]. Model updating consists of updating the baseline model based on experimental output of the structure. The modified AIS algorithm was called AISWA and a comparison between this method and a method called fuzzy logic damage detection was done. These methods are explained more in Section 4.6 due to their applicability to process data from both local and global damage detection techniques.

At the 24th international Ocean and Polar Engineering Conference in June 2014, Diao, Chen, Ren and Sun from Qingdao Technological University published a conference paper on structural damage alarming on offshore platforms based on the principal components of the transmissibility function (TF) [91]. TF is defined as the ratio between two measured responses in the frequency domain. Hence, excitation forces were not measured and since the acceleration responses were directly used, no FE-model or modal parameters were needed. A change of structural properties resulted in a change in TF. The theoretical idea behind this concept is explained below as presented in [91]. Starting with the equation of motion for an excited structure:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = f(t) \tag{4.20}$$

Here M is the mass matrix, K is the stiffness matrix, C is the damping matrix and $F(t)$ is the excitation force. The displacement vector is denoted x, so that the first derivative $\dot{x}$ is the velocity and second derivative $\ddot{x}$ the acceleration.

The response of this developed system can be interpreted with respect to frequency in a frequency domain by the following equation:

$$[-\omega^2 M + i\omega C + K]X(\omega) = F(\omega) \tag{4.21}$$

Here, $X(\omega)$and $F(\omega)$ are the FTs of $x(t)$ and$f(t)$. By defining $H(\omega)$ as the ratio between the output and the input of the system:

$$X(\omega) = H(\omega)F(\omega) \tag{4.22}$$

The frequency response spectrum (FRF) is obtained:

$$H(\omega) = [-\omega^2 M + i\omega C + K]^{-1} \tag{4.23}$$

Changes in mass, damping or stiffness will affect the FRF. Damage can have an impact on mass and stiffness of the structure, making the FRF a tool for assessing damage by comparing new and old FRF. To evaluate FRF, the excitation forces (input) needs to be known. When doing ambient measurements (unknown input) it is possible to make use of the transmissibility function (TF). Therefore an acceleration vector $A(\omega)$ is obtained by performing differential operation on (4.21):

$$A(\omega) = [-\omega^2 H(\omega)F(\omega)\ ] \tag{4.24}$$

By assuming a single excitation $F_k(\omega)$ located in the input degree of freedom k, the TF is obtained between the acceleration response $A(\omega)$ in point i and j.

$$T_{ij} = \frac{A_i(\omega)}{A_j(\omega)} = \frac{-\omega^2 H_{ik}(\omega)\{F(\omega)\}}{-\omega^2 H_{jk}(\omega)\{F(\omega)\}} = \frac{H_{ik}(\omega)}{H_{jk}(\omega)} \tag{4.25}$$

Here, $H_{ik}(\omega)$ and $H_{jk}(\omega)$ are measured FRFs between output degree of freedom i and j, whilst k is the input degree of freedom. From this it can be seen that TF only depends on location of the excitation force, but not amplitude. In other words, it is possible by using TF to identify damage without the unknown input. A statistical procedure was used to extract the principal components of the TF by doing a principal component analysis (PCA). The method was tested numerically on a jacket model using FE-modelling software ANSYS. The paper concludes that this developed method is very suitable for online SHM. The fact that this method did not need a FEM-model is the main reason for their conclusion.

To this date, most of the problems related to vibration based damage detection on offshore jacket structures have been solved numerically. However, there are no examples of these methods tested on a large scale offshore jacket structure. When locating damage in a dynamic environment, measurement and processing uncertainties is still a challenge. Table 4-8 is a summary of the degree of damage identification that was discussed in Section 2.2.2 related to global damage measuring techniques. What comes very clear from Table 4-8 is that at least three vibration based damage detection methods fully qualify the three first levels of damage detection. None of the vibration based damage techniques proposed to this date can give a prognosis containing remaining life estimation (level 4). Further assessment needs to be done based on FM theory. Strain or fatigue gauges are the two types of gauges that can measure and give input to the FM theory.

TABLE 4-8: OVERVIEW OF VIBRATION BASED DAMAGE DETECTION ON OFFSHORE JACKETS

Damage detection method	Degree of damage identification	Remarks
Frequency change (Vandiver)	Level 1	Not optimal for use on offshore jacket structures
Mode shape (Rubin and Coppolino)	Level 1	Need to be tested on a real jacket structure
Mode shape (Shahrivar and Bouwkamp)	Level 1	Need to be tested on a real jacket structure
Mode shape (Kim and Stubbs)	Level 3	Need to be tested on a real jacket structure
MSEC (Shi and Law)	Level 2	Need to be tested on a real jacket structure
Compliance (Choi, Park and Stubbs)	Level 3	Potentially applicable on offshore jacket platform
MSEC+CMSE (Amiri, Asgarian and Ghafooripour)	Level 3	Needs to be further calibrated to be used on a real structure
Bicoherence function (Hillis and Courtney)	Level 2	Need to be tested on a real jacket structure and damage localization need to be added
TF (Diao, Chen, Ren and Sun)	Level 2	Need to be tested on a real jacket structure and damage localization need to be added

4.5 Data Processing Methods

Processing of the collected data is an important step in a monitoring system. There is a variety of processing methods, and the literature survey brought attention to the most frequently used in addition to some newly developed methods. The objective of this section is therefore to look at the basics of these which all can be used in SHM systems of offshore jackets. For additional information regarding these methods, it is referred to the papers referenced in the following text. Table 4-9 includes the processing methods and their applications. It is clear that most of the methods are related to modal analysis.

Table 4-9: Data processing algorithms used in SHM of jackets

Processing Methods	Application
Fatigue rainflow cycle counting	Fatigue life evaluation
Fourier Transform (FT/FFT)	Modal analysis
Short Time Fourier Transform (STFT)	Modal analysis
Wavelet Transform (WT)	Modal analysis

The right method to use relies on the type of sensors that produces the data to be processed. The fatigue rainflow counting methods are used in correlation with strain gauges to extract the stress cycles followed by a calculation of the damage by using Miner's rule [74]. On the other hand, the FT/FFT, STFT, WT and WPT algorithms from Table 4-9 are used when a conversion to frequency domain is needed. Commonly this is needed when accelerometers are used during modal analysis.

There are several stress cycle counting techniques. Reservoir counting, range method, zero-crossing range method, and rainflow counting are those found in literature. During the monitoring of Forties Bravo platform [45] the range, zero-crossing and rainflow methods were used and they proved that the rainflow counting was the most conservative method. According to knowledge obtained from DNV GL, the rainflow counting is also the most used method. The procedure is to transform variable amplitudes in an S-N curve to constant amplitudes. This results in for example number of cycle's pr. day which is a linear input of the Miner's rule for evaluating the remaining fatigue life. Miner's rule was defined in (3.3).

When it comes to the vibration based damage detection, it relies on identifying the dynamic modal properties by using transformation methods from time domain to frequency domain. FT or the alternative version fast Fourier transform (FFT) is one of those transforms and the process is illustrated in Figure 4-12 (A) [7]. The function in the time – amplitude plot gets broken down into its different frequencies, and showed in the frequency-amplitude plot. This result in a graph that can be easier understood and evaluated. (4.26) and (4.27) defines the integrals used to either convert from time to frequency domain or simply the inverse.

$$\mathrm{F(v)} = \int_{-\infty}^{\infty} \mathrm{f(t)e^{-2\pi ivt}dt} \tag{4.26}$$

Inverse FT:

$$\mathrm{f(t)} = \int_{-\infty}^{\infty} \mathrm{F(v)e^{2\pi ivt}dv} \tag{4.27}$$

Where:

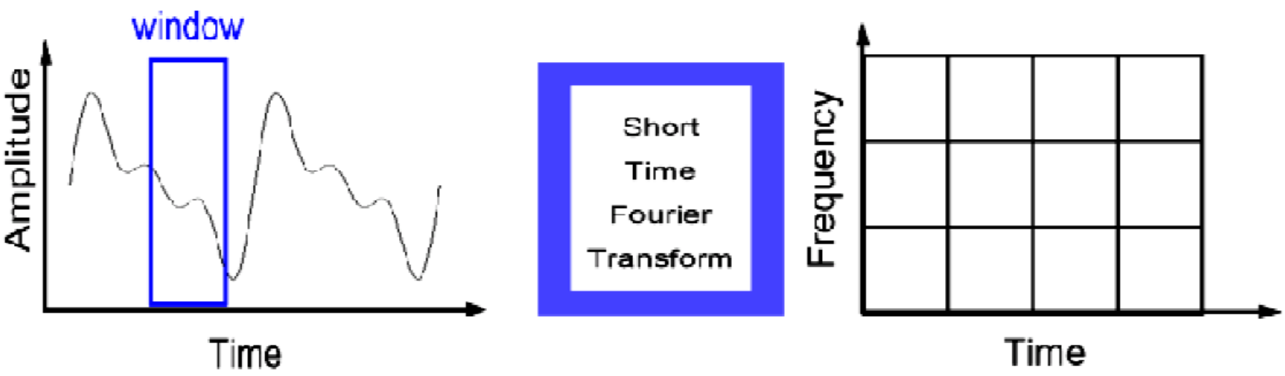
$$v = \frac{\omega}{2\pi}[Hz] \tag{4.28}$$

And ω is rad/s.

A crack is typically a structural damage that vibration based damage detection aims to detect. To detect a crack at a single point, the need of detecting high frequency signals is introduced. This means that monitoring of higher modes should be done. The STFT was proposed as a better algorithm to process high frequency signals by dividing the signal in windows and process one of these windows at a time. STFT analyse the signal in a constant resolution, and do not take into account the different characteristics of high and low signals in the processing [7]. Figure 4-12 (B) illustrates the windowing technique and the constant resolution [7]. WT is a relatively new way of analysing the frequencies, doing processing with different resolution dependent on the signal characteristics [92]. This means that the WT technique can adjust the resolution on any frequency interval, hence be able to detect variations in the signal where the other techniques with constant resolution fail. Figure 4-12 (C) illustrates the adjustable resolution in the WT processing [7].

It is observed trough literature that vibration based damage detection methods with the aim of monitoring higher modes is limited. Based on the information above regarding the data processing method, it is obvious that methods for evaluating higher frequencies have been developed. This means that the data processing methods are a step ahead of the development of vibration based testing of offshore structures.

(A)FT DESCRIPTION



(B)STFT DESCRIPTION

(C) WT DESCRIPTION

FIGURE 4-12: A, B, C ILLUSTRATIONS OF DIFFERENT TRANSFORMS

4.6 Data Evaluation Models

The processed data needs to be evaluated so that it is possible to answer the four levels of data evaluation in a SHM system. As presented in Section 2.2.1, these are:

Level 1: Determination that damage is present in the structure

Level 2: Level 1 plus determination of the geometric location of the damage

Level 3: Level 2 plus quantification of the severity of the damage

Level 4: Level 3 plus prediction of the remaining service life of the structure

A quantitative assessment of these four levels can be obtained with models. Typically these models also recognise and disregard noise in the signals. Numerical models recognized during the literature survey are listed below:

- Fuzzy logic system
- Artificial immune system (AIS)
- Artificial Neural Network (ANN)
- Statistical

A paper has been made comparing fuzzy logic system and AIS to damage detection on a jacket model in operational condition [90]. It is observed that these two models can be used on offshore jacket structures and both models have a high success rate even though noise is present due to the operational environment offshore. Applications of damage evaluation models are also found in SHM of other industries. For instance a paper revising the methods of fuzzy logic and ANN on composite helicopter rotor blades has been made [93]. Statistical methods have also been recognized in literature. One example of that is that the statistical damage evaluation method was tested on a bridge in Switzerland [94]. Following is a general description of the models and Table 4-10 summarizes the different positive and negative aspects of each one of them.

Fuzzy logic system is a damage detection and evaluation model which uses values from 0-1 to evaluate if-then rules. This method differs from what is called binary values that are either of 0 or 1. In other words, the fuzzy logic can present the degree of truth. For instance, instead of identifying that a cup of coffee can be either empty or full (0 or 1), it can classify the degree of fullness (or emptiness) in the cup with numbers between 0-1. This means that the fuzzy logic can make decisions based on detailed knowledge, hence be a powerful tool in damage evaluation [90, 93].

AIS is a damage detection model based on the human immune system. AIS models are using learning and memory capabilities to improve its damage detection model. This means that detailed training of the model is necessary before it can be used. However the second time a familiar scenario appears, the AIS will have a quick response [90].

ANN is a network consisting of artificial neurons. These neurons need to be activated to send information further. Activation doesn't get initiated if the weight of the received signal is low. Hence, the increase of weight induces an increase of the signal strength. This is the fundamental idea behind ANN. Mathematical functions determine the activation based on the incoming weighted signals whilst another function computes the actual output after activation [95].

Statistical damage evaluation uses the difference in the mean values and standard deviation based on statistical distribution of the received data. A failure will induce a change in these parameters, making this method able to detect failures in a SHM system. Based on this, the model is useful for anomalies happening often, however rare anomalies can be more difficult to address [94].

TABLE 4-10: DAMAGE DETECTION MODELS

Model	Positive aspects	Negative aspects
Fuzzy Logic System (FLS)	- Relatively high success rate - Computationally lower cost than AIS - Efficient	- Lower success rate than AIS - Need rule development
Artificial Immune System (AIS)	- High success rate - High efficiency - Efficient - Noise immunity	- Detailed training of the model - Computationally higher cost than FLS
Artificial Neural Network	- High success rate - Efficient	- Long training time needed
Statistical	- High success rate - Slow	- Requires a large amount of data - Not suitable for rare anomalies

4.7 Main Suppliers of Offshore SHM Technology

During the literature survey, these technology suppliers have been recognized:

- FUGRO
- VALLEN
- Strainstall
- HBM
- PULSE
- FORCE

These companies can deliver complete SHM systems, from sensors to data processing facilities which potentially can be used on offshore jacket platforms. In the following an overview of their systems and applications are discussed.

In addition to local NDT services as for example FMD detection, FUGRO deliver global structural monitoring systems. They have a product called On Line Monitoring (OLM) [80]. According to their catalogue this system is said to detect stiffness changes of a fixed platform by monitoring the change in natural frequency. The dynamic characteristics are afterwards compared with an agreed acceptance criteria developed by FUGRO for the customer. There is no further available information about which data processing methods and damage evaluation algorithms that is used. The background for choosing change of natural frequency as a damage indicator is not stated. The reason for choosing frequency change can probably be due to the fact that this system doesn't aim to localize damage, only detect. A typical installation includes accelerometers placed in various locations and a wave-radar to compare the structural response to the wave loading. The OLM system is installed 30 times and The Ninian Southern Platform on NCS has continuously been monitored in 20 years.

VALLEN is another system contributor on the market which has specialized in AET systems [96]. According to their webpage, VALLEN explains their use of the AET technique due to these factors:

- AET can detect actively growing cracks
- AET can locate hidden and remote flaws
- AET is one of the few NDT techniques that can be used for long-term continuous monitoring

The VALLEN system is developed for many industries, and papers assessing the application of this system on offshore jacket structures are limited. However an example of the use of their AET system on jacket structures was explained in Section 4.3.1. In that paper the AMSY-6 software was used in addition to VALLEN AE sensors, AE preamplifiers and AE signal processor. However this was just an experimental approach, no case studies of the VALLEN AET system used on offshore jacket structures are available in literature. The whole product chain is presented in Figure 4-13 [96].

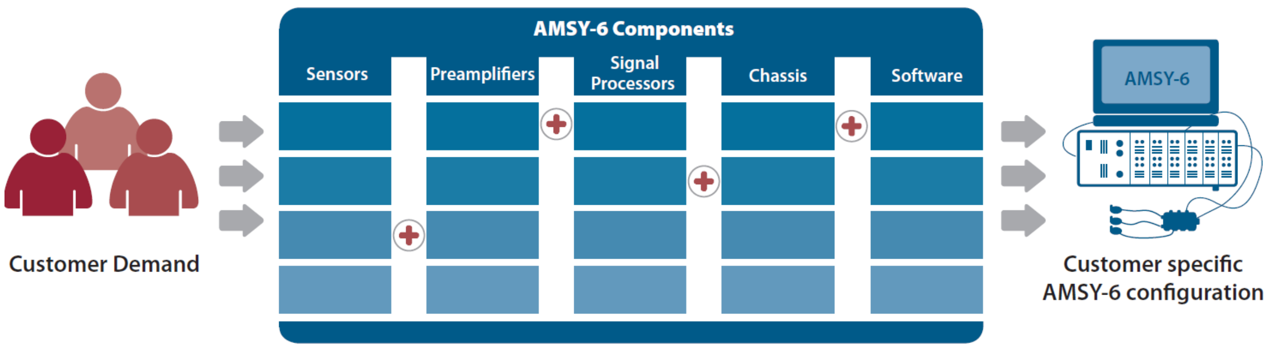


FIGURE 4-13: THE VALLEN PRODUCT CHAIN

Strainstall is a supplier of SHM systems for mainly civil structures and case studies on successful use of their systems are mainly focused on bridges. The product that may have a potential for the use on offshore jacket structures are the CrackFirst™ fatigue gauge that was elaborated on in Section 4.3.2. According to the webpage of Strainstall and articles [74, 97] the CrackFirst™ system has proved efficient for measurements on welded joints exposed to stress cycles on offshore wind platforms in the UK. The substructure of the wind turbines was monopiles, however the case study is a good measure of the applicability of the CrackFirst™ fatigue gauge.

HBM delivers a system where they develop the measurement setup, selects and installs the suitable sensors and cables, operates the measurement system and provides for the analysis of the measurement data. The applications are mainly related to mechanical systems. No case studies of their monitoring system tested on jacket structures are available.

PULSE is a supplier specialized on the offshore industry. They have delivered their platform integrity systems since 1998 [98]. Their instrument catalogue contains accelerometers, inclinometers (measuring tilt) and strain gauges. In addition they deliver wave radar instrumentation for environmental monitoring. Real time software provides instant integrity information. There is no information available of which type of data processing methods and damage evaluation algorithms that is used. In 2012/2013 the Valemon jacket in the North Sea was monitored with the use of PULSE technology. A case study was published illustrating the instrumentation and results.

5. SHM Methodology Proposal for an Offshore Jacket Platform

The purpose of this chapter is to develop a general cost effective monitoring methodology for offshore jacket structures. According to NORSOK N-005 [33] the detailed condition monitoring programme of loadbearing structures depends on:

- *design and maintenance philosophy*
- *current condition*
- *capability of the inspection methods available*
- *intended use of the structure*

In the following a flowchart is produced illustrating a proposal for the procedure of the design and implementation of a SHM system on to a jacket structure. This is followed by an explanation of the different steps.

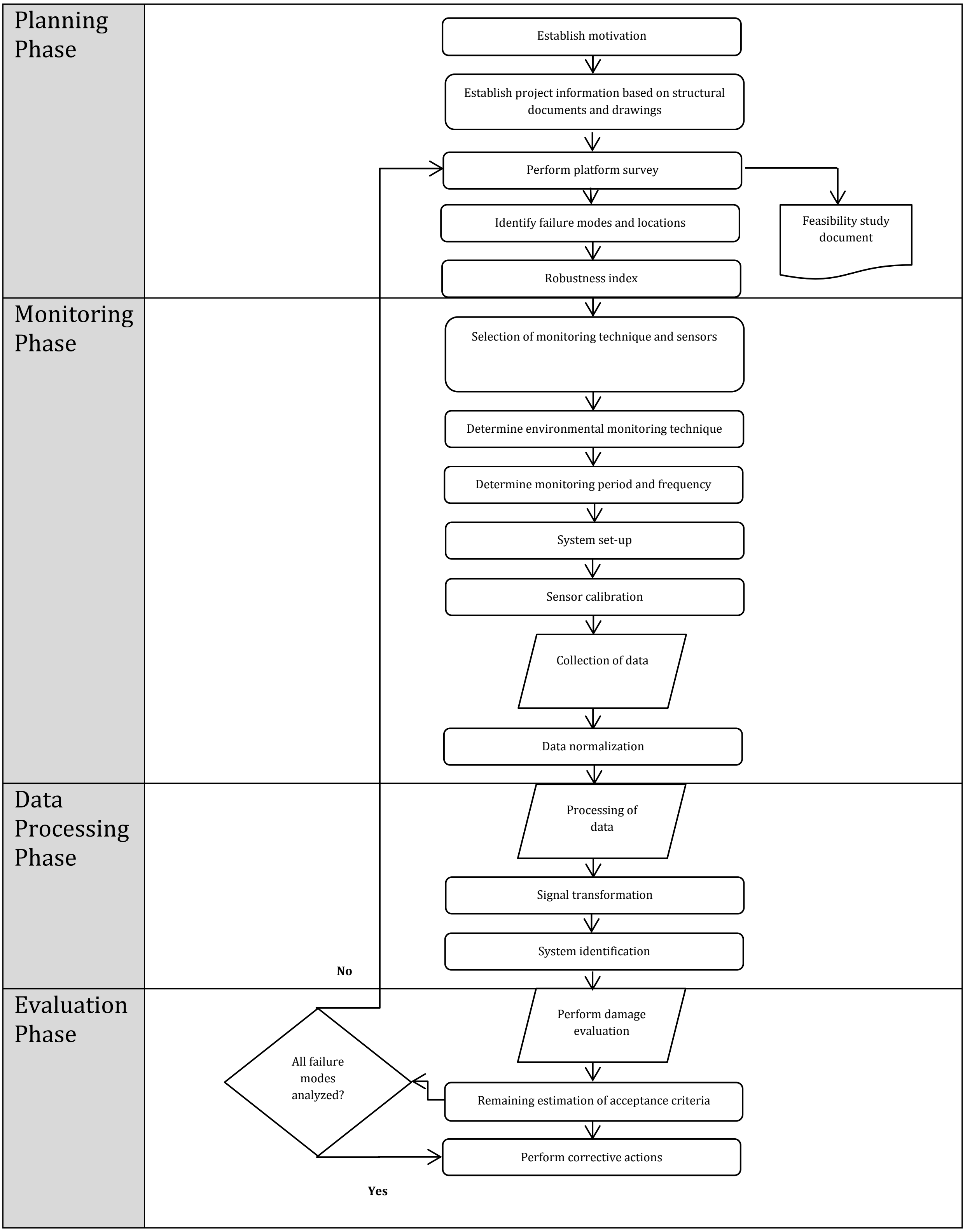


FIGURE 5-1: FLOWCHART OF THE SHM METHOD

5.1 Planning phase

Establish Motivation

The first thing any asset owner has to do before considering investing in a SHM system is to establish a motivation. Throughout history and even today SHM of offshore structures have been very expensive and according to papers available a relatively small amount of jackets are equipped with a SHM system globally. This means that the majority of jackets today use manual monitoring, most likely based on a RBI approach. By looking at the bigger picture, SHM can result in reduced cost due to its capability to show proof of allowance to increase the life of the assets. ISO 19902 [21] contains a table where motives for inspection on a jacket structure are stated:

- *Fabrication defects or installation damage.*
- *Degradation or deterioration of the structure.*
- *Design uncertainties or errors.*
- *Environmental or weight overload.*
- *Accidental events.*
- *Changes in permanent actions.*
- *Monitoring of known defects or repair effectiveness.*
- *Change of ownership.*
- *Statutory requirements.*
- *Reuse.*

Establish project information based on structural documents and drawings

Before identifying critical failure modes of the structure, collection of data need to be performed. In NORSOK N-006 Section 5.2 [44], a list of the information that shall be available for assessment of offshore structures is given. The list is made to count for all offshore structures therefore the list below is modified to only include the information needed for a steel jacket platform:

- *As built drawings of the structure.*
- *New information on environmental data, if relevant.*
- *Permanent actions and variable actions.*
- *Previous and future planned functional requirements.*
- *Design and fabrication specifications.*
- *Original corrosion management philosophy.*
- *Original design assumptions.*
- *Design, fabrication, transport and installation reports which should include information about material properties (e.g. material strength elongation properties and material toughness test values), weld procedure specifications and qualifications, modifications and weld repairs during fabrication, non-destructive testing (extent and criteria used), pile driving records (action effects during pile driving and number of blows).*

- *Weight report that is updated during design life.*
- *In-service inspection history including information on marine growth, corrosion, cracks, dents and deflections, scour damages due to frost, impact, erosion/abrasion, leakages.*
- *Information on in-place behaviour including dynamic response (measurements and observations).*
- *Information and forecast for seabed subsidence*
- *Information on modifications, repair and strengthening to the structure during service life.*
- *Soil conditions, pore pressure and consolidation.*
- *Slope instability, erosion at pile foundations, differential settlement.*
- *Experience from similar structures.*

Information regarding the technical facilities and installation procedures can be found in the plan for development and operation (PDO), plan for installation and operation (PIO), design fabrication installation (DFI) and documents for operation (DFO). According to NORSOK N-006, the information that is not available should be replaced with assumptions on the safe side.

Perform Platform Survey

A platform survey described in the paper by Duthie and Gabriels [53] in Section 4.3.1 is a procedure that should be performed before implementation of any type of SHM system. This survey results in an understanding of how exactly the sensors should be placed, the amount of sensors needed and routing of cables. Pictures taken from the platform have to be collected. This visit results in a feasibility document which shall be basis for the system set-up.

Identify Failure Modes and Locations

It is referred to Section 3.3 for identification of failure modes and the respective damage parameters occurring on a jacket structure. According to NORSOK N-005 [33], to be able to identify critical locations and key components for the structural integrity of a jacket structure, ULS analysis with a FE-model is recommended. Critical locations are places where for example a structural detail with new structural design, or where equipment recently has been installed. The accident in 1980 at the Alexander Kielland platform in the North Sea is an example of the importance of monitoring such locations [99]. A newly installed hydrophone was the cause of the development of fatigue cracks on the platform leading to platform collapse. Also an ULS analysis is used to locate hotspots where especially fatigue damage is more likely to occur. According to NORSOK N-006 special care should be taken to the splash zone, because of the high risk of fatigue damage due to wave loads. Ship collisions may also happen in this area.

Robustness Assessment

A nonlinear analysis of the jacket structure should be performed in order to assess the robustness of the structure [100]. This can be done by a so called pushover analysis. The nonlinear pushover analysis is done by adding load from waves and gravity to the structure, and increase the horizontal wave loads until collapse. This analysis is potentially already done during design of the jacket. The following structural redundancy index (SR) and residual strength factor (RSF) should be checked:

$$SR = \frac{CL_i}{L_{fi}} \tag{5.1}$$

$$RSF = \frac{CL_{di}}{CL_{nd}} \tag{5.2}$$

The collapse load is denoted CL_i and L_{fi} is the load when first member failure occurs. CL_{di} and CL_{nd} is the collapse load of the ith member in damaged condition and the collapse load of the structure in undamaged condition. The SR value indicates the difference between the overall collapse load of the structure and the load at the first failed member. Of that reason the SR value is a good measure of the structural robustness. RSF indicates the reduction in capacity from damaged to undamaged state. In other words the degree of redundancy and damage tolerance increases with increased values of SR and RSF.

5.2 Data Collection Phase

Selection of Monitoring Technique and Sensor Technology

An assessment on which type of damage identification technique that should be used is needed. Both local and global monitoring techniques should be used to capture all the failure modes and obtain redundancy in the monitoring system. More information about this is described in Section 2.2.1 and 2.2.2 .

In addition determination of data processing method and evaluation method is critical so that the data can be properly processed and interpreted. It is referred to Section 4.5 and 4.6 for different processing and evaluation methods suitable for monitoring of offshore jackets.

When researching the methodology for implementing monitoring systems for CM in [5] the applicability of modifying the MPN procedure to be used to compare the different monitoring techniques was evaluated. However it proved to be an insufficient way to assess the most suitable techniques because there are so many uncertainties and alternatives affecting the selection. In addition SHM does not use the amount of sensors that is used in CM, hence the procedure may be unpractical. The MPN procedure is described in Appendix B. Table 4-7 in Section 4.3.4 was developed instead as a guide for selecting the right sensor with regards to noise immunity, mounting configuration, WSN compatibility and maturity.

Determination of Monitoring Period and Frequency

Determination of sampling frequency and monitoring period is an important step, and is specific for each sensor. In general high sampling frequency is needed for short time failures and low sampling frequency for long time damage identification. It is important to obtain a balance between high enough frequency to avoid aliasing and as low sampling frequency as possible to avoid unnecessary computational effort.

The sampling periods also needs to be established. It is possible to perform continuous or periodic monitoring. The data processing capacity needs to be designed with regards to how much data storage is needed.

System Set-up

System set-up involves installation of sensors, wiring (if needed) and data acquisition system. It is of high importance to make sure that that the location of the sensor not becomes a source of crack growth.

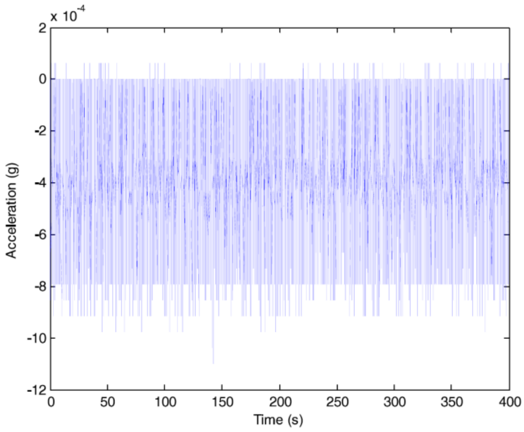
Perform System Calibration

After installation on the platform, the system should pass a site acceptance test described in the paper by Duthie and Gabriels [53] and from the monitoring of Magnus by Webb and Corr [49]. With reference to what was stated in Section 4.3.1, this test shall include the following checks: system response from a repeatable electronic source (AE-sensor only), sensor response with the system, remote control of the workstation, data transfer, and software function checks including alarm and warning functions.

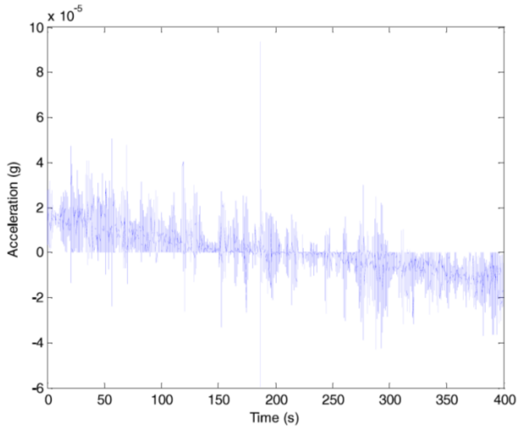
Data Normalization

Data normalization should be performed before processing of the data to extract the signal data without noise and also account for sensor malfunctioning. Figure 5-2 illustrates a signal in time domain with environmental noise (A) and sensor malfunctioning (B) [94]. When comparing these two with Figure 5-2 (C) the importance of data normalization becomes clear. (5.3) is an equation used for data normalization [94]. Here $x(t)$ is the signal in time domain, whilst μ and σ is the mean and standard deviation of the signal. By letting the signal data be processed by a data normalization algorithm an acceptable time history can be obtained.

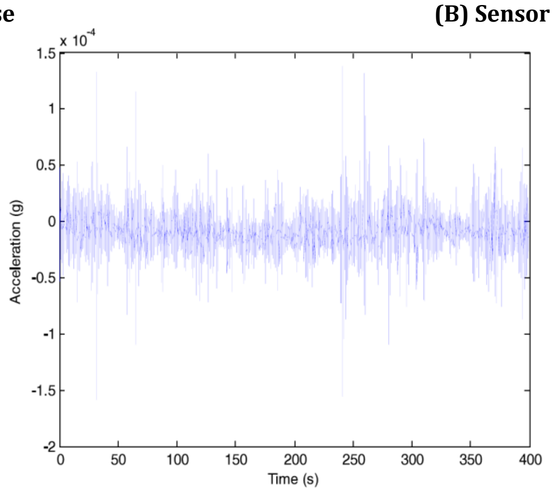
$$x(t) = \frac{x(t) - \mu}{\sigma} \tag{5.3}$$



(A) Noise



(B) Sensor malfunctioning



(A) Acceptable time history

FIGURE 5-2 A, B AND C: EFFECT OF DATA NORMALIZATION

5.3 DATA PROCESSING PHASE

Signal Transformation

This step is important for the SHM systems. The signal in time domain has to be transformed to frequency domain with data processing methods. The processing techniques are described in Section 4.5 and their applicability is discussed. The evaluated processing methods are:

- Fatigue rainflow cycle counting
- Fourier Transform (FT and FFT)
- Short time Fourier transform (STFT)
- Wavelet transform (WT)

System Identification

The task of identifying the damage indicator which is sensitive to damage from the vibration response is needed. This may be the most important process in the SHM system due to the fact that it is here the structure is defined as damaged or undamaged.

5.4 Evaluation Phase

Damage Evaluation

Damage evaluation consists of using the damage evaluation methods described in Section 4.6 to evaluate the damage from the processed sensor data. The vibration based damage detection is divided in the four levels as described in Section 2.1.1. These four levels were:

Level 1: Determination that damage is present in the structure

Level 2: Level 1 plus determination of the geometric location of the damage

Level 3: Level 2 plus quantification of the severity of the damage

Level 4: Level 3 plus prediction of the remaining service life of the structure

The evaluation techniques described in Section 4.6 are:

- Fuzzy logic system
- Artificial immune system (AIS)
- Artificial Neural Network (ANN)
- Statistical

Remaining Estimation of Acceptance Criteria

Identification of acceptance criteria is the process of assessing the acceptance of damage for the monitored damaged elements on the jacket. This depends on type of element for instance weld, tubular joint etc. General guidelines are given in NORSOK N-006 [101].

Corrective Actions / Mitigating Measures

Corrective actions are based on the results from the damage evaluation. The corrective actions can be mitigating measures, or even a decision to decommission the structure. According to NORSOK N-006 [101], the following mitigating measures for fatigue cracks can be done:

- *reduce loading, e.g. replace members, remove inactive conductors, appurtenances, marine growth*
- *reduce stress level by strengthening, e.g. install new members, clamps*
- *reduce stress concentrations, e.g. by internal grouting of tubular joint*
- *improve fatigue capacity by improvement methods*

- *perform controlled in-service inspections such that cracks are detected before they are through the wall thickness such that they can be removed by grind repair methodology*

6. CASE STUDY

The aim of this chapter is to show the applicability and discuss cost of a SHM system on a fictional offshore jacket structure on the NCS. The proposed monitoring plan is based on monitoring techniques and sensors evaluated in Chapter 4 and the methodology presented in Chapter 5. The result includes:

- Description of sensors
- Description of data processing, evaluation models and their facilities
- An outline of how the data from the monitoring can be used in evaluation of the structural integrity of the structure

During the literature survey it was recognised that there were a considerable amount of new research, but a lack of examples where the new measuring methods was used on a real jacket structure. After thorough consideration it was concluded that the case study should be divided in two parts. First a monitoring plan with mostly confirmed applicability on real offshore jacket structures is proposed. In the second part two alternative set-ups is discussed to show the applicability of new research discovered during the work of this thesis.

The motive is to describe a SHM system set-up that measures damage parameters and failure modes of the jacket. With that being said, this is just a theoretical approach and the instrumentation set-up may have to be changed if it was to be used on a real offshore jacket structure. Structural details and practical problems that are hard to predict theoretically are examples of sources that may result in changes to the actual system set-up.

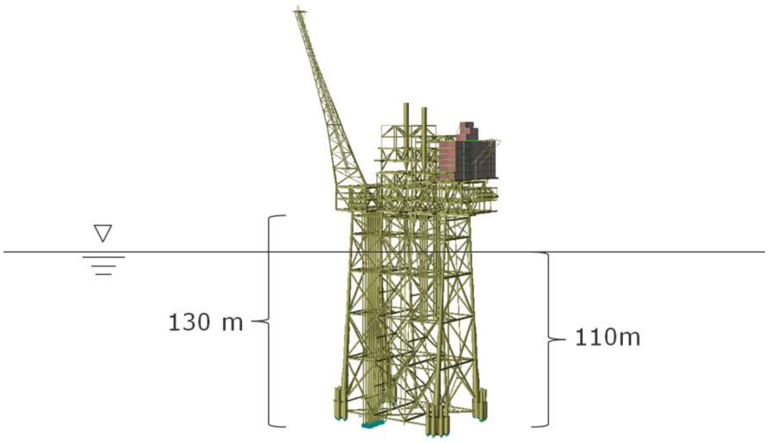


FIGURE 6-1: FICTIONAL PLATFORM FROM GENIE SOFTWARE

The platform being assessed in this case study is a fictional platform located on the NCS. Height of the substructure of the platform is assumed to be 130 m, and the water depth is 110 m. The platform was installed with clustered pile configuration at each corner leg.

6.1 PLANNING PHASE

The jacket structure is located on the NCS and is assumed to be halfway into its initial assigned design life. The proposed SHM system will therefore be adapted to the structure and no imbedded sensors will be used. The motivation for installing a SHM system on this jacket can be divided in two:

1. Continuous monitoring of the integrity of the structure
2. Use the data history obtained from the measurement period to calibrate design calculations to real data from this location

These two parameters will potentially make the asset owners save cost. Dependent on the result, the monitoring can prove an extension of the initially assigned lifetime. It will also result in reduced cost on jackets built in the future by potentially decreasing design factors. It is the first point that will be evaluated in this case study.

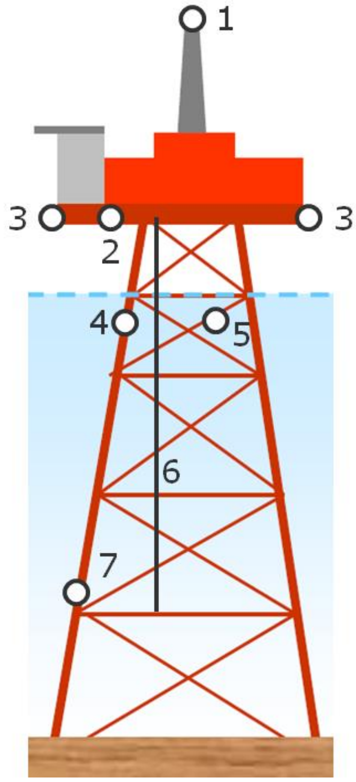
When the motivation is developed, information and related documents from the specific platform is collected and evaluated. Since this is a fictional platform, these documents cannot be obtained. However, assumptions are made. According to the operational history of the jacket there is one severed brace in elevation -71.50 m. It is assumed that cracks are observed as a consequence of fabrication error. No accidents of importance have occurred during transport or operation. Furthermore no other fabrication failures have been reported. This means that there is at least one location on the structure that needs special consideration in addition to locations with high SCF subjected to variable loading.

Due to the assumptions made from the information gathering, it is mainly failure modes caused by fatigue damage, corrosion and change in flexibility due to reduced pile performance that is needed to be measured in this context. The reason for this is that those failure parameters are directly related to degradation of the jacket. In addition the severed member needs to be monitored so that it is possible to assess the crack propagation. From Section 3.3.1 it is stated that fatigue damage typically accumulates as cracks in riveted and welded connections. In addition, from Section 3.3.2 the location with highest risk of corrosion damage is in the splash zone. At this point the failure modes of importance have been established. In addition the general locations of these failure modes are mapped.

The jacket considered is of bracing pattern Type 6 ref. Figure 3-2. This means that the tubular joints have good shear resistance, which leads to less shear deflections [29]. According to DNVGL-RP-C210 [102], jackets with four legs or more are rather redundant structures when X-type bracing is used. It is not possible to calculate SR (5.1) and RSF (5.2) with the resources available. For simplicity it is assumed that it is possible to monitor a frequency change with the first three modes.

6.2 MONITORING PHASE

Figure 6-2 is a simplified illustration of the system set-up [27]. The purpose of this illustration is to obtain an instant overview of the instrumentation on the platform.



1: Anemometer

2: Wave radar

3: Accelerometer

4: Current meter

5: Fatigue gauge

6: Tension cable

7 : AE-sensor

FIGURE 6-2: GENERAL SYSTEM THE SET-UP

As stated in Section 5.2, today both global and local damage detection techniques should be used to be certain that all the critical failure modes have been accounted for during monitoring and to obtain redundancy in the monitoring system. A global damage measuring technique as the vibration based damage detection is capable of monitoring change in dynamic behaviour of the jacket structure caused by member severance. This may be fatigue, dents or other parameters affecting the dynamic properties. On the other hand, the local damage detection technologies evaluated in Section 4.3 can monitor the local cracks and strain.

The global monitoring technique used for this case study is vibration based damage detection aimed to discover change in the monitored frequency. This method is chosen because its applicability has been documented on a jacket structure in the North Sea and it uses software that is available today [51]. Due to relative low cost, robustness and immunity to harsh weather conditions FBG accelerometers are chosen. Environmental loads subjected to the jacket structure are important to measure with regards to uncover conservative design and to compare global response and loads. Therefore two wave radars in each corner on one side are chosen to be installed on the topside of the platform. Also, an anemometer is proposed to be located on the flare tower. Finally, a current meter is installed right below the sea surface on the same side as the wave radars. This environmental instrumentation set-up is influenced by the set-up used on the Ekofisk platforms [47].

The local damage detection technologies are chosen to be AE-sensors and fatigue gauges. The AE-sensors will be used to monitor crack propagation at the severed member. The fatigue gauges is chosen instead of strain gauges to obtain structural response. The reason for this is because it is interesting to illustrate and discuss the output coming from this sensor.

The cost reduction obtained by using a WSN is due to no need of wiring and reduced installation time. Research on the applicability of WSN for structural vibration monitoring from 2008 was found [103]. However, water proving and reliability issues was parameters that needed improvement. In addition, the test was only done on a model and not on a real jacket structure during operation. Only one monitoring project using WSN on a real offshore jacket structure was found during the literature study [66]. However, limited information about the set-up was obtained. In addition it has not been available information about any further experiments with WSN on offshore jacket structures. There is also no thorough description on the use of wireless AET sensors on real jacket structures available. Of that reason the following monitoring plan consists of wired sensors.

Table 6-1 is a presentation of the chosen instrumentation. The sampling periods and frequencies are based on information given in the product catalogues and from the OTC report of the instrumentation of the Ekofisk platforms [47]. However, it is not certain that the given sampling frequencies are the most optimal frequencies for their purpose.

TABLE 6-1: INSTRUMENTATION PLAN

Detection capability	Sensor type	Sampling frequency	Length of time series	Sampling intervals	Comments
Wind speed	Anemometer	10 Hz	17 minutes	3 hours	
Water particle velocity	Current meter	5 Hz	17 minutes	3 hours	
Wave elevation	Wave radar	5 Hz	17 minutes	3 hours	
Deck displacement	Accelerometers	200 Hz	60 minutes	3 hours	x- and y-direction
Fatigue crack	AET	1 MHz	-	Hit based	
Fatigue	CrackFirst™	N/A*	-	Continuous	

*information not available

Since crack growth is one of the failure modes of concern the sampling intervals are done periodically with a relatively short time interval. In Table 6-2 to Table 6-4 the sensor specifications are listed. The information is taken from available online information about the sensors [97, 104, 105].

Table 6-2: AE sensor

Sensor	AET sensor
Product name	VS150-WIC-V01
Description	VS150-WIC-V01 is a piezoelectric watertight AET sensor with integrated preamplifier. The sensor is protection rated to be used in up to 60 bar which equals approximately a water depth of 587 m. The product can be found in the product catalogue of VALLEN systeme. The sensor supports automatic sensor testing.
Illustration	
Mounting	Surface mounted No cleaning required

Table 6-3: Acceleration sensor

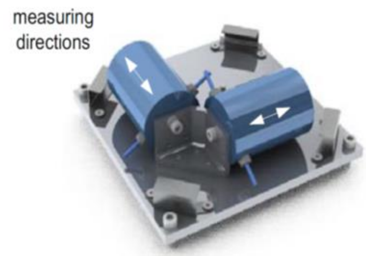
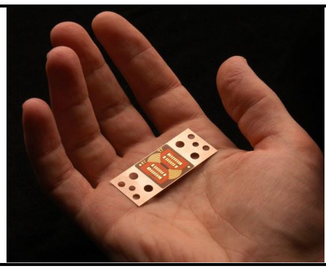
Sensor	Accelerometer
Product name	FS 65
Description	FS 65 is an optical accelerometer based on the FBG technology. It is suitable for measuring ambient induced vibration of structures. The sensor is IP68 rated. This means that it is watertight but should be placed in a box for additional protection
Illustration	
Accessories	Surface mounted

Table 6-4: Fatigue gauge

Sensor	Fatigue gauge
Product name	CrackFirst™
Description	CrackFirst™ is a fatigue gauge with a pre-crack able to predict remaining fatigue life at welded connections. Only available from Strainstall. The installation area can be sealed to be protected from corrosion and mechanical damage.
Illustration	
Mounting	Surface mounted

A set-up is based on the platform survey performed in the planning phase. Figure 6-3 is an overview of the jacket with numbered elements. This figure is the basis for the explanation of the location of the sensors.

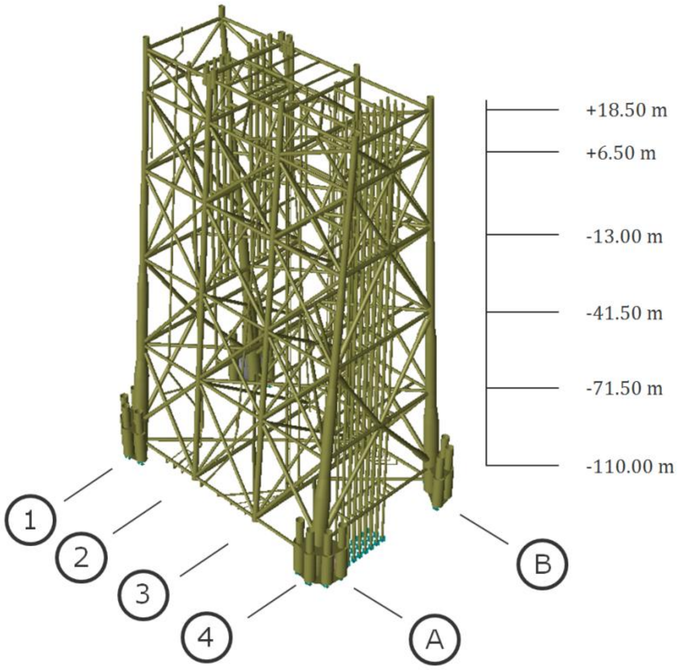


FIGURE 6-3: JACKET OVERVIEW

The vibration based damage detection set-up used in this case study is influenced by the instrumentation of Ninian platform in the North Sea [51]. As discussed in Section 4.2, this set-up has proved suitable for detecting member severance on an offshore jacket structure. Accelerometers are placed on the four corner legs in location 1A, 1B, 4A and 4B on elevation +18.5 m. The set-up is seen in Figure 6-4.

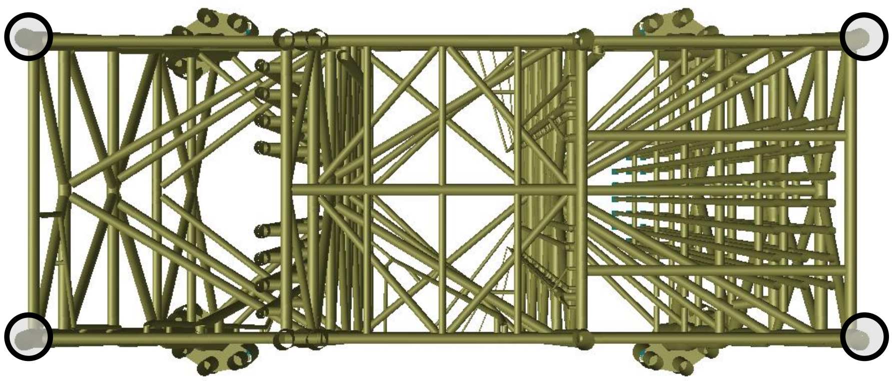


FIGURE 6-4: LOCATION OF ACCELEROMETERS

AE sensors are placed on the severed member near node 4A in elevation -71.50 m. The reason for deploying the AE sensors in this location is to monitor potential crack propagation on the severed member with proven cracks. Four sensors are placed around the node. The cables from the sensors are collected in a box which is connected to a tension cable attached to a winch on the topside for simple installation. The use of a tension cable has been proved to be a suitable and simple solution for this type of instrumentation set-up [50].

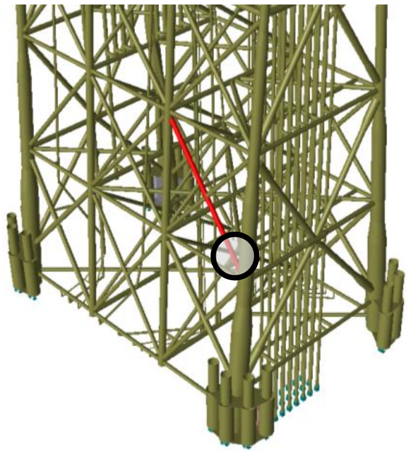


FIGURE 6-5: SEVERED MEMBER IN ELEVATION -71.50 M

From Section 3.3 it is proven by statistics that the majority of the cracks reported on jacket structures occurs on the nodes. CrackFirst™ fatigue sensors are placed on reference nodes on the jacket structure, up to 10 mm from the weld in the node [35]. These nodes have to be seen as representative elements for the other nodes on the jacket. The reason for using these sensors is to get a real time overview of the damage accumulation. New design details should also be considered instrumented with a CrackFirst™ fatigue sensor to distinguish any uncertainties in their fatigue life performance. It is stated that the CrackFirst™ sensor is made for joint class F from BS 7608 [106]. It is also stated that the sensor can be used on joints in the class above and below F with satisfying result [107]. These classes are E and F2. Unfortunately BS 7608 has not been available from the University library or from DNV GL. However, to illustrate the capability of this type of sensor it is assumed that it can be fitted to a pair of reference nodes on the jacket and cables can be installed along the main legs. These nodes are selected to be 3A in elevation -13.00 m and the joint between A and B in row 4 in elevation -13.00 m. The locations are illustrated in Figure 6-6.

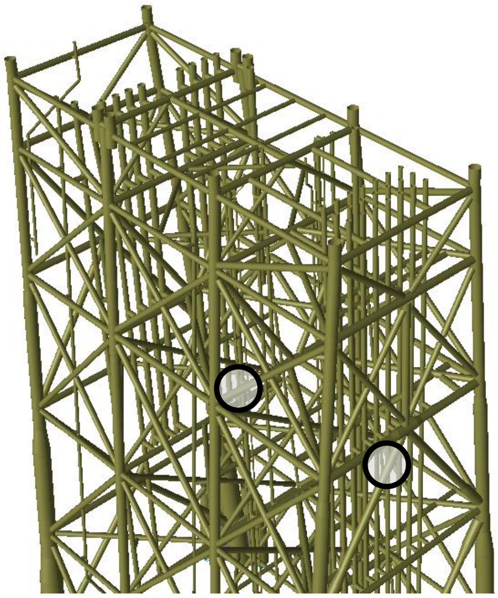


FIGURE 6-6: CRACKFIRST™ LOCATION

Attention is needed in the splash zone. As stated in Section 3.3.2, the splash zone is where corrosion is most likely to occur. To date, it seems like there are no sensors that easily can be installed in the splash zone for corrosion measurements. According to the earlier mentioned report which looked at the technology advancements in the field of integrity assessment for the offshore industry, UT and visual inspection is the methods that should be deployed in this region [35].

Calibration is needed before the monitoring system can be started. As explained in Section 5.2, system response from a repeatable electronic source (AE-sensor only), sensor response with the system, remote control of the workstation, data transfer, and software function checks including alarms need to be performed.

6.3 DATA PROCESSING PHASE

According to [51], software provided by Fugro can be used to identify spectral peaks and natural frequencies from a response spectra made from signals in periods of one hour. The kind of data processing method used is not specified. Since the aim is to detect the three first modes a FFT is suitable. If the aim was to detect higher modes the wavelet transform would possibly be more suitable due to the adjustable resolution. In addition to save the former mentioned data, all the raw data is stored. Also backup of the data is stored onshore in case any information is lost. The software and hardware is installed in a cabinet in a control room of the platform.

Three data analysis tools can be provided by VALLEN. These are called VisualAE, VisualTR and VisualClass. Their capabilities are explained in the following but for more detailed information please see the AMSY-6 product catalogue [52]. VisualAE is software capable of doing data analysis and presentation. VisualTR is software that is capable of investigating data in detail by the use of FFT or wavelet transform and it generates training data to the VisualCass software which uses statistical analysis to discover damages from the signal. For the purpose of this case study, it would save computational effort and storage needs by introducing a hit based data acquisition. According to the AMSY-6 catalogue, a hit is defined as when the acoustic emission signal crosses a pre-defined threshold [52]. This means that processing of data only commence when a so called hit occurs and ends after the last threshold crossing.

6.4 Evaluation Phase

The data from the vibration based damage detection system is presented in Atkins fleet management system (FMS). FMS is a web based tool used by the operators to evaluate structural integrity. The system can download data from the monitoring system on the platform. In Figure 6-7 the monitoring data is presented as seen in the FMS software [51]. The presented data is of a five year measurement for one mode. In Section 4.4 parameters affecting the frequency change was stated. From Figure 6-7 it is easy to establish at least three parameters affecting the signal.

Firstly, in the hourly measured frequencies there might be a lot of noise. To reduce noise three different mean values where used. As seen on top of the frequency plot in Figure 6-7 the mean values are from 4 hours, 24 hours and 28 days. A similar plot is produced for each of the three first dynamic modes of the jacket structure.

Secondly, the frequency shift is affected by the top side mass changes. A threshold of predefined min and max values is therefore used. This threshold is represented by the green area. A frequency shift beyond this threshold will indicate severe damage and normally not any mass changes in normal operational condition.

Thirdly, there might be instruments on the topside inducing frequencies similar to the natural frequency of the offshore jacket structure. Such an event is illustrated in the upper middle of the plot in Figure 6-7.

Even though the three former mentioned parameters may affect the structural diagnosis, it is possible to get an indication of a severed member. In the lower left, a severed brace that have induced a frequency change is displayed. When a frequency changes beyond the threshold values, an alarm will be activated. In the case of Figure 6-7 there was a 3% frequency change.

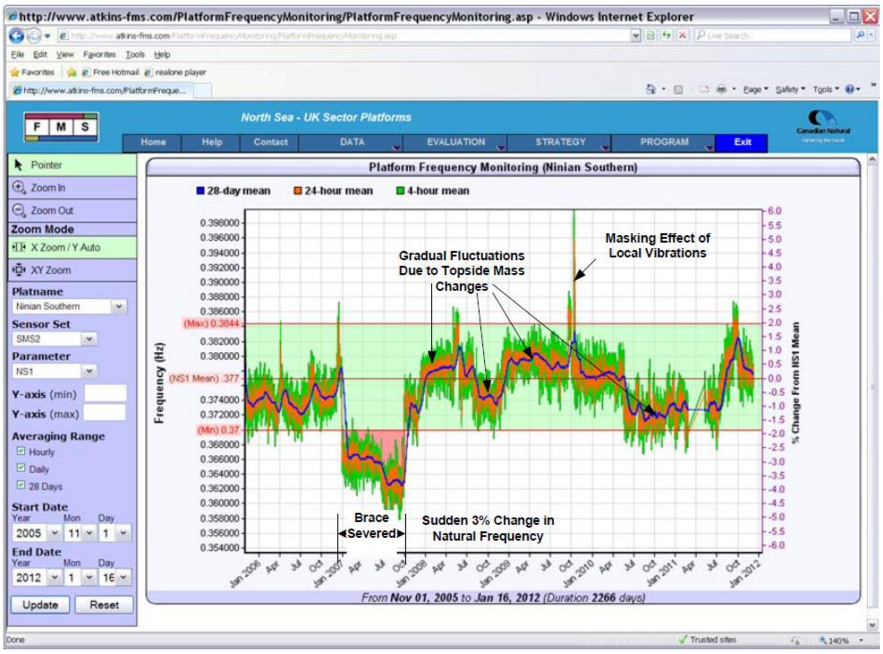


FIGURE 6-7: FMS RESULT PRESENTATION

In this case study also the VALLEN AMSY-6 software is used due to its compatibility to the VALLEN sensors. Also here an automatic warning and alarm signal will initiate at different levels of signal amplitude. Figure 6-8 illustrates the features extracted from a reading [52]. As in Figure 6-7, it is also a predefined threshold which is the base for an alarm or warning signal if the frequency increases above the threshold. Duration, rise-time, peak amplitude and threshold crossing counting are the parameters that can be read from the display. This means that if crack propagation occurs at the severed member of our jacket, the asset owner will be notified. The notification will be an alarm or warning message dependent on the amplitude of the AE signal.

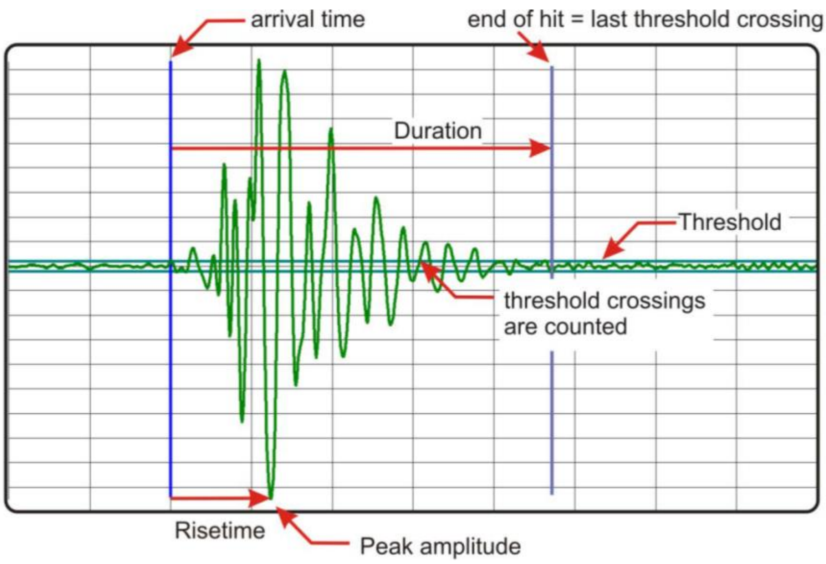


FIGURE 6-8: EXTRACTED FEATURES IN AMSY-6

From the CrackFirst™ sensors, a real-time S-N presentation can be obtained, making the asset owners capable of predicting the real-time remaining fatigue life of the reference nodes on the jacket. Table 6-5 is describing the typical sensor data obtained by the CrackFirst™ sensor [73]. Sensor status is denoted with the numbers 1 or 0. 1 describes an intact sensor and 0 describe a malfunctioning sensor. The crack length represented by number of intact tracks is registered on the left and right hand side of the pre-crack. The accumulated fatigue damage is calculated according to the appropriate joint class of BS 7608 [106]. The sensor data below is a result of a complete fatigue test from crack propagation until rupture.

TABLE 6-5: TYPICAL SENSOR DATA

Reading	**Sensor status**	**Crack length left hand side** No. of intact tracks	**Fatigue damage Class F (%)**	**Crack length right hand side** No. of intact tracks	**Fatigue Damage Class F (%)**
1	1	12	0	12	0
2	1	11	7	12	0
3	1	10	13	11	7
4	1	9	21	10	13
5	1	8	28	9	21
6	1	7	38	8	28
7	1	6	49	7	38
8	1	5	58	6	49
9	1	4	67	5	58
10	1	3	74	4	67
11	1	2	81	3	74
12	1	1	90	2	81
13	1	0	100	1	90

As explained in this section, from the outputs of the different monitoring techniques it is possible to get a general overview of the structural integrity of the structure. Also, the AE-sensors give the asset owners the possibility to monitor crack propagation in high critical areas in real time. However, the splash zone is an area where corrosion will not be detected with this SHM system. This result in believing that a set-up depending on mature technology in the offshore industry, is not able to cover all the areas where regular manual monitoring are focused today.

6.5 DISCUSSION

The proposed monitoring plan consists of a combination of local measuring techniques and global measuring with the use of vibration based damage detection. The set-up is partly based on the technology available today in addition to a new fatigue gauge that can be very effective for real time fatigue life evaluation if more testing is done. It needs to be confirmed that the fatigue gauge can be used on nodes connecting tubular welded joints. Also the applicability of the subsurface robustness with regards to corrosion and pressure need to be tested. Moreover it is shown that accelerometers are not needed to be installed under the sea surface if the aim is to detect the three first dynamic modes of the offshore jacket structure. The software and their applications from Fugro and Atkins are illustrated. The application and installation of AE sensors with the use of VALLEN products are also proposed to be used on high critical locations. Together the sensors and software can result in a general assessment of the structural integrity of the jacket structure.

If the robustness of the jacket structure is relatively low, the proposed SHM system can be suitable for this kind of monitoring situations. However, as stated in Section 4.4 using the frequency change as a damage indicator is not optimal. There are many uncertainties as for example mass change and other general operational parameters that can affect the measurements. As seen in Figure 6-7 the threshold needs to be comprehensive due to topside mass change which leads to inaccuracy. In the OTC report where this set-up was used, it was stated that the accelerometers could detect a severed member if it induced a frequency change of more than 2% [51]. This means that severed members that induce a lower frequency change than 2% will be remained undetected. In addition, if this system was being installed on a jacket with higher redundancy, more modes are going to be needed to be measured [100]. This results in installation of an increased number of accelerometers which needs to be installed under the sea surface. It is believed that when the offshore industry gains more information and can really see the opportunities of SHM systems, more suppliers will enter the market resulting in higher competition and lower costs. Even so, an instrumentation set-up based on several instruments below sea surface should be performed with a WSN to reduce installation cost further.

The monitoring plan that was presented represents how far the technology has come today. In the following two monitoring plans that are believed to be more cost effective and robust is presented. The first are using technology which may be used in the near future and the last being a monitoring plan with technology that represent what SHM may look like further into the future.

6.5.1 FUTURE CASE 1

In the following, the potential of an alternative monitoring plan and vibration based damage detection method is discussed. It is observed through literature that increased robustness of a jacket structure leads to the necessity of identifying higher order modes in order to assess failure in secondary elements [100]. To obtain higher order modes more accelerometers is needed to be distributed on the jacket structure. This means that accelerometers need to be installed under the sea surface. In Section 4.3.1 it is stated that FBG sensors have high range, is water and corrosion resistant, immune to harsh weather conditions and have reasonable cost. This results in the belief that the FBG technology is a suitable option for subsurface monitoring [65]. Connecting FBG sensors in a wireless network could result in a very robust and cost effective system. Figure 6-9 illustrates the main elements in the WSN set-up [65]. Here the FBG sensors are illustrated and the process of uploading the data to terminals. In this case the terminals are represented by a central control unit or from terminals as laptops or even phones. As stated in Section 6.2, there are at least one example of this kind of set-up combining FBG sensors and WSN on an offshore jacket structure in China [66].

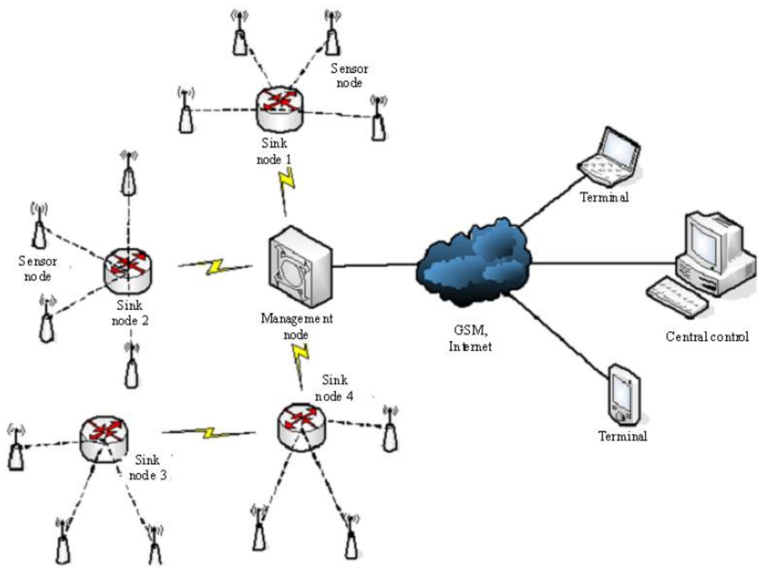


FIGURE 6-9: WSN SET-UP OF FBG SENSORS

The vibration based damage detection method in the proposed monitoring plan in Section 6.2 was restricted to only detect damage. No direct information about location was obtained. A vibration based damage detection method that may have a potential in that regard is the methods that aims to calculate the MSEC as stated in Section 4.4. According to the experiments done with this method it has proven to be robust in locating both single and multiple damages in a structure [88]. The results are even obtained with different levels of added noise. The disadvantage with this method is that accelerometers need to be placed in each node of the jacket structure. However by combining this method with a WSN using FBG sensors, such an installation could possibly be performed to a reasonable cost.

An instrumentation set-up as explained above will result in an increased amount of data that needs to be processed. However, in Section 4.3.3 it is stated that the FBG sensors can be used as MEMS. This would result in a localized data processing regime and only the important data is sent to the centralized computer making the level of computational effort less. This idea is illustrated in Figure 4-8. It is important to be aware of that if the MEMS technology is introduced, this result in also introducing the problems related to MEMS. As stated in Section 4.3.3 these are related to the limited CPU power which slows down the system and makes it difficult to obtain a real time monitoring system. Also limitations with regards to battery power are introduced.

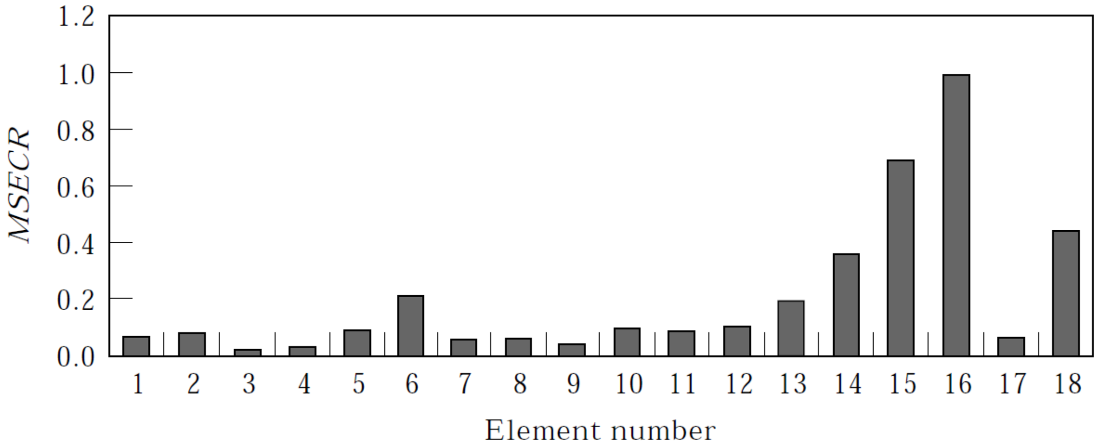


FIGURE 6-10: DAMAGE LOCALIZATION

The proposed monitoring plan may result in a real time evaluation of the member severance of the jacket in addition to their location. Figure 6-10 illustrates the presentation of the MSECR calculations as seen in the article by Shi, Law and Zhang [84]. In this particular scenario both member No.15 and No.16 was severed. This is represented in Figure 6-10 with high MSECR values for those two elements. As a concluding remark, this kind of set-up may in theory work, but it is important to remember that these methods have not been tested on real jacket structures so it is believed to be many uncertainties.

6.5.2 Future Case 2

Vibration based testing has its limitations when used in an offshore environment. Acoustic fingerprinting may not suffer from the mass and operational changes of the jacket structure and therefore it may be an appropriate replacement as an alternative global damage detection method. The general functions of the acoustic fingerprinting are explained in Section 4.3.3.

The acoustic fingerprinting technology with the reflecting method had its limitations, but is absolutely an interesting concept. The idea of doing damage localization below sea surface by installing equipment above the sea surface is something worth investigating further due to the cost reduction and all the practical benefits that goes with having the equipment on the topside. There have not been found further proof of any testing that indicates that this method is viable on a real jacket structure. According to the last HSE report the next step is to test the system on a real offshore jacket to assess design of sensors, optimize signal drift reduction, assess the influence of background noise and assess the potential of frequency change of topside mass redistribution [76]. Getting answers to these problems will make it easier to compare the performance of the two global damage detection methods, namely acoustic fingerprinting and vibration based damage detection.

Figure 6-11 illustrates how the set-up might look like on a leg of a real jacket structure. In the experimental tests they installed transducers on the main legs. In addition, a PZT configuration was installed in the same location.

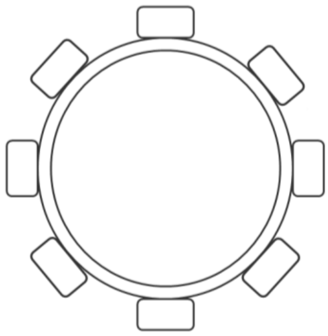


FIGURE 6-11: ACOUSTIC FINGERPRINTING SET-UP

The cost of using an acoustic fingerprinting system is unknown. However the installation procedure is relatively simple because all the instruments are placed above the splash zone. Since the sensors are placed above the splash zone, only wiring from the sensors to the workstation is needed. This information may indicate that the installation cost will be relatively low. Maintenance cost should also be regarded as low since the sensors are located at highly available locations.

7. Conclusive Remarks and Recommendations for Further Work

7.1 Conclusive Remarks

A literature study of the SHM methodology in general has been performed, and important definitions have been explained. Also, SHM in different industries have been evaluated. The usage and importance of offshore jacket platforms have been described together with their structural characteristics and failure modes. It is shown that the failure modes of a jacket are many, but crack propagation caused by fatigue is according to statistics the most frequent parameter influencing the structural integrity of the jacket structure. Results from the literature study of SHM for offshore jacket structures are presented. This includes research of sensor technologies for jacket structures that are either proven, unproven or state of the art. It is no doubt that there are many different technologies to choose from, each with different characteristics as shown in Table 4-7. The use of the different sensors is dependent on which failure modes and damage parameters that the instruments are supposed to monitor and the environment the sensors are being installed in.

In addition, damage indicators, data processing methods and data evaluation algorithms was explained and evaluated. A proposed methodology for SHM of jacket structures was developed. Further the methodology was used on a fictional platform on NCS. A monitoring plan was developed with a combination of new and proven technology. In addition, the implementation of two alternative monitoring plans for the future was discussed. The SHM system can in theory be able to evaluate a satisfying degree of structural integrity of a jacket structure with the technology available today. However, a combination of local and global measuring techniques should be used. One area of concern is the splash zone, which there are no specific sensors developed for evaluating corrosion.

According to research, acoustic fingerprinting may outperform the vibration based damage detection techniques. Dynamic characteristics are suitable for damage detection on a structure with redundancy below a certain level, but for the noisy environment offshore and the operational conditions with for instance change of topside mass, acoustic fingerprinting may be more suitable.

The cost related to implementation of a SHM system is discussed. It is most likely the installation and maintenance cost that differs the cost of the different monitoring systems. It is believed that when the field of SHM grows and the offshore industry really see the potential of SHM systems, more suppliers will enter the market resulting in higher competition and lower costs.

7.2 FURTHER WORK

Based on what is observed throughout the work of this thesis, some recommendations for further work are given in the following.

- It is quite clear that the proposed vibration based damage detection methods described in this thesis should be tested on real offshore jacket structures. It is difficult to evaluate the different techniques and come with recommendations when the methods are not proved to work sufficiently in the operational conditions of an offshore jacket structure.
- The CrackFirst™ fatigue sensor should be tested for subsurface applicability and suitability for welded tubular joints.
- Research effort should be focused on new technology as MEMS and smart dust to obtain more information about robustness and better data processing performance for the microprocessor.
- Further testing on the acoustic fingerprinting system to evaluate the suitability in operational conditions.
- Development of sensors able to detect corrosion damage in the splash zone.

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A. Appendix – Overview of Distributors

Table A-1: Sensor Distributors

Sensor	Distributor
AET	Vallen Systeme GmbH Schaeftlarner Weg 26, 82057 Icking, Germany Phone: +4981789674-400 Fax: +4981789674-444 Mail: info@vallen.de http://www.vallen.de/products/multi-channel-systems
Foil Strain Gauge	KYOWA [Foil strain gauge] 3-5-1, Chofugaoka, Chofu, Tokyo 182-8520, Japan Phone: +81-42-485-6714 Fax: +81-42-486-1436 http://www.kyowa-ei.com/eng/index.html
Vibrating Wire Strain Gauge	Geokon (Norwegian representative, Geonor AS) [Arc weldable vibrating wire strain gage] Grinidammen 10 N-1359 Eiksmarka, Norway http://www.geokon.com/
Fatigue Gauge (CrackFirst™)	Strainstall [CrackFirst™ fatigue monitoring] Fisher House PO Box 4, Barrow-in-Furness Cumbria LA14 1HR, UK Mail: enquiries@strainstall.com http://www.strainstall.com/

Sensor	Distributor
Piezoelectric Strain Gauge	HBM [Piezoelectric strain] HBM, Inc. 19 Bartlett Street Marlborough, MA 01752 USA Phone: 800-578-4260 Fax: 508-485-7480 Mail: info@usa.hbm.com http://www.hbm.com/en/
FBG Sensor	HBM Phone: +47 48 300 700 http://www.hbm.com/en/
Electrical Resistance based corrosion Sensors	Metal Samples Company P.O. Box 8 152 Metal Samples Rd. Munford, AL 36268 Phone: (256) 358-5200 Fax: Mail: msc@alspi.com http://www.alspi.com/
Flooded Member Detection (FMD)	Fugro TSM (Fugro's Subsea division) The TCM department have offices in: Perth WA 6000 Phone: +61 8 9218 2000 Singapore 509015 Phone: +65 6227 2298 KL, Malaysia 50250 Phone: +603 2166 2433 Miri, Sarawak, Malaysia 98000 Phone: +60 85 662 445 Email: info@fugrotsm.com

Sensor	**Distributor**
Guided Wave Testing	Olympus KeyMed House Stock Road SS2 5QH Southend-on-Sea, UK Phone: +44 (0) 1702616333 Fax: +44 (0) 1702 465677 Email: info@olympus.co.uk http://www.olympus-ims.com/en/
Acoustic Fingerprinting	N/A*
Smart Sensor System	Bosch Sensortec GmbH Gerhard-Kindler-Strasse 9 72770 Reutlingen, Germany Phone: +49 7121 35 35900 Email: contact@bosch-sensortec.com http://www.bosch-sensortec.com/

*Information not available

B. APPENDIX – MPN TABLES

MPN is a procedure described in ISO 13379 [5]. The procedure is proposed to assist the selection of monitoring technologies in correlation to different failure modes. The MPN number is made up of 4 different parameters. The parameters are explained in the following:

- Rating detection (DET) indicates the likelihood of the failure mode to be detected with the selected monitoring technique. This is estimated on a scale from 1 to 5:

  1: There is remote likelihood that this failure mode will be detected.
  2: There is a low likelihood that this failure mode will be detected.
  3: There is a moderate likelihood that this failure mode will be detected.
  4: There is a huge likelihood that this failure mode will be detected.
  5: It is virtually certain that this failure mode will be detected.

- Severity of failure (SEV) is an indicator ranking the failure modes by risk. This is estimated on a scale from 1 to 4:

  1: Any event which could cause degradation of system performance function(s) resulting in negligible damage to either system or its environment, and no damage to life or limb.
  2: Any event which degrades system performance function(s) without appreciable damage to either system or life or limb.
  3: Any event which could potentially cause loss of primary system function(s) resulting in significant damage to the system or its environment, and/or cause the loss of life or limb
  4: Any event which could potentially cause the loss of primary system function(s) resulting in significant damage to the system or its environment, and/or cause the loss of life or limb

- Diagnosis confidence (DGN) is an indicator of how well the monitoring technique can diagnose the failure mode. This is estimated on a scale from 1 to 5:

  1: *There is a remote likelihood that this failure mode diagnosis will be accurate*
  2: There is a low likelihood that this failure mode diagnosis will be accurate
  3: There is a moderate likelihood that this failure mode diagnosis will be accurate
  4: There is a high likelihood that this failure mode diagnosis will be accurate
  5: It is virtually certain that this failure mode diagnosis will be accurate

- Prognosis confidence (PGN) is an indicator of the accuracy of the prognosis from the monitoring technique. This is estimated in a scale from 1 to 5:

  1: There is a remote likelihood that this failure mode prognosis will be accurate

  2: There is a low likelihood that this failure mode prognosis will be accurate

  3: There is a moderate likelihood that this failure mode prognosis will be accurate

  4: There is a high likelihood that this failure mode prognosis will be accurate

  5: It is virtually certain that this failure mode prognosis will be accurate

The numbers are multiplied resulting in a MPN number as defined:

$$MPN = DET \cdot SEV \cdot DGN \cdot PGN \qquad \text{B.1}$$